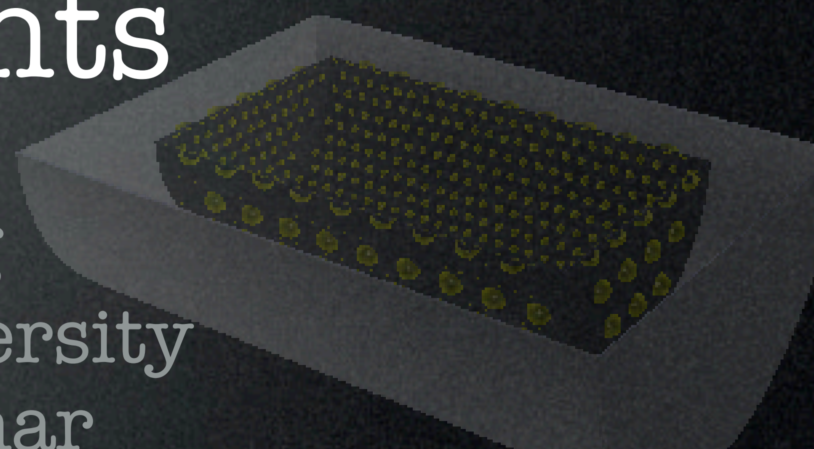
NuPRISM:
An Experimental Method to Remove Neutrino Interaction Uncertainties from Oscillation Experiments



Mike Wilking
Stony Brook University
Fermilab Seminar
May 12th, 2016

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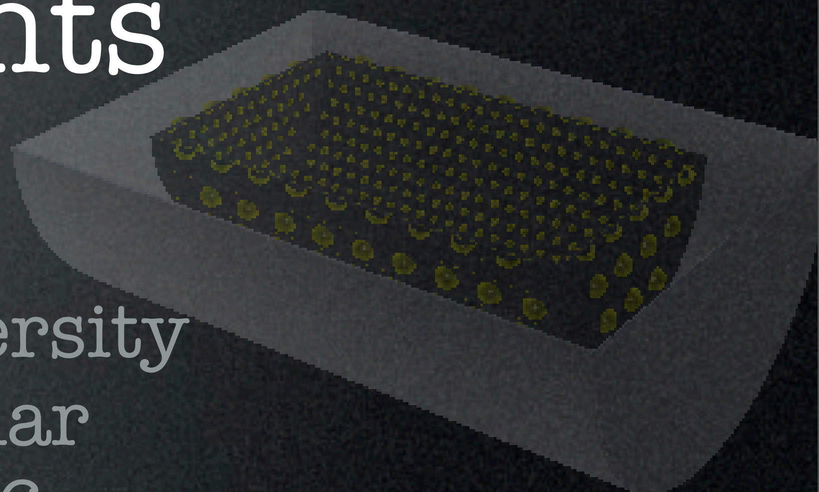
NuPRISM: An Experimental Method to Remove Neutrino Interaction Uncertainties from Oscillation Experiments



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Neutrino Mixing

Flavor States

Mass States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Atmospheric ν"

(Super-K, K2K, MINOS)
θ_{23} = 45°±6° (90% C.L.)

"Reactor ν"

(Daya Bay, RENO, Double CHOOZ)
θ_{13} = 9.0°±0.5°

"Solar ν"

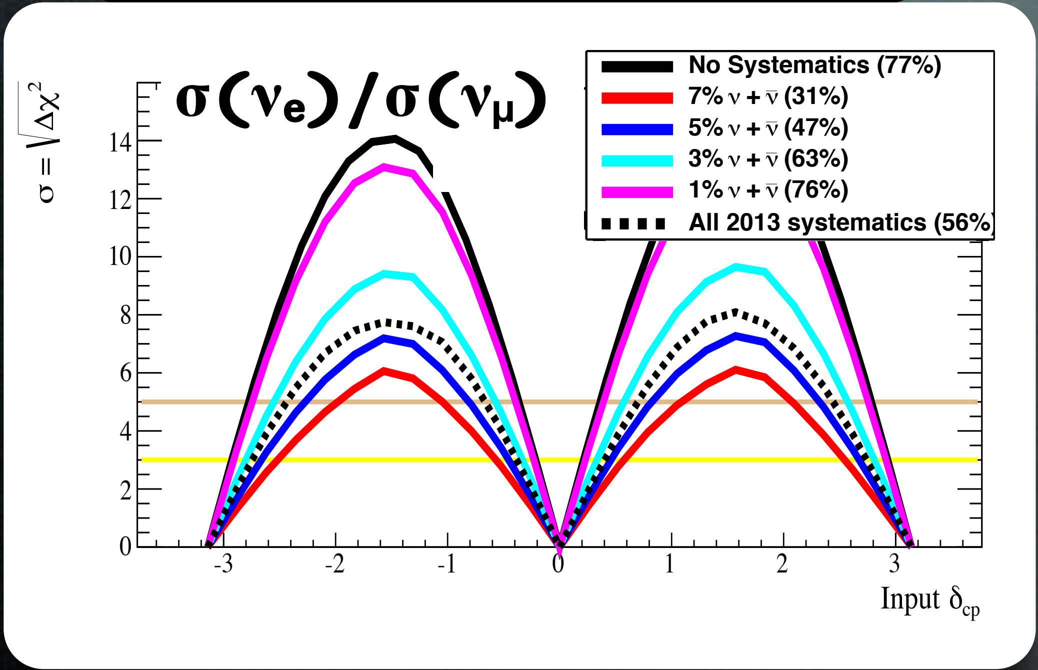
(SNO, KamLAND)
θ_{12} = 33.9°±1.0°

Majorana phases; Not yet observed

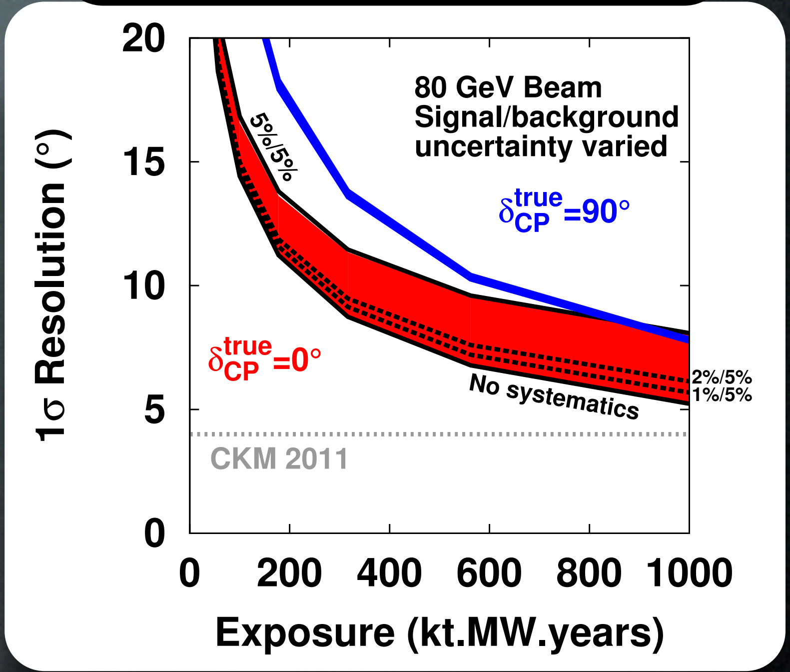
- All 3 neutrino mixing angles are now well known
  - Largest uncertainty is in θ_{23} (may still be maximal)
- Main focus of current and next generation long baseline neutrino experiments is to measure δ_{CP}
- Additional goals include further improvements to mixing angles and mass splitting (e.g. Δm_{32}^2), and the determination of the neutrino mass hierarchy

Defining "Precision δ_{CP} Measurements"

Hyper-Kamiokande



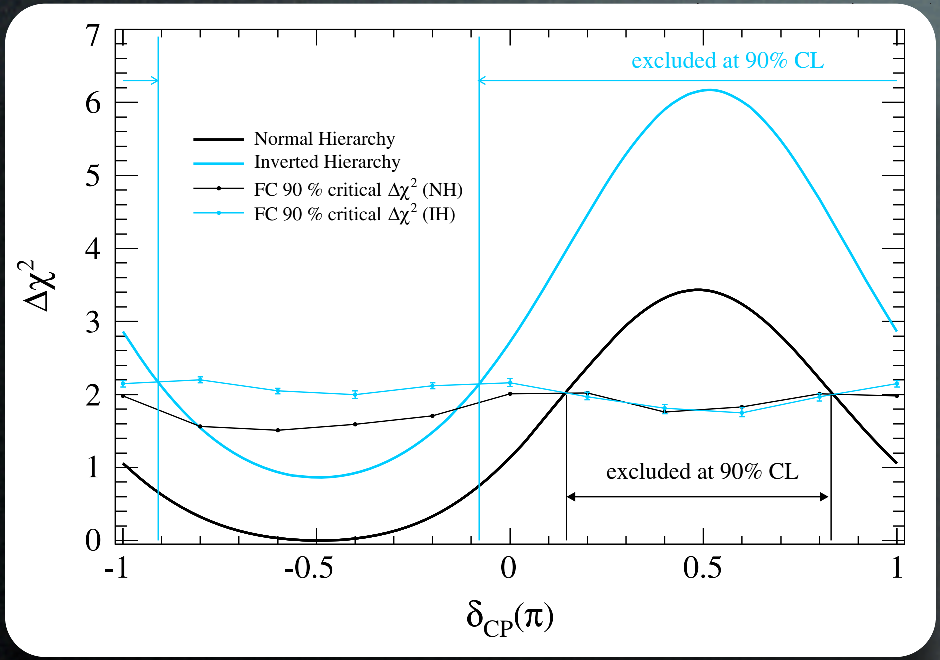
DUNE



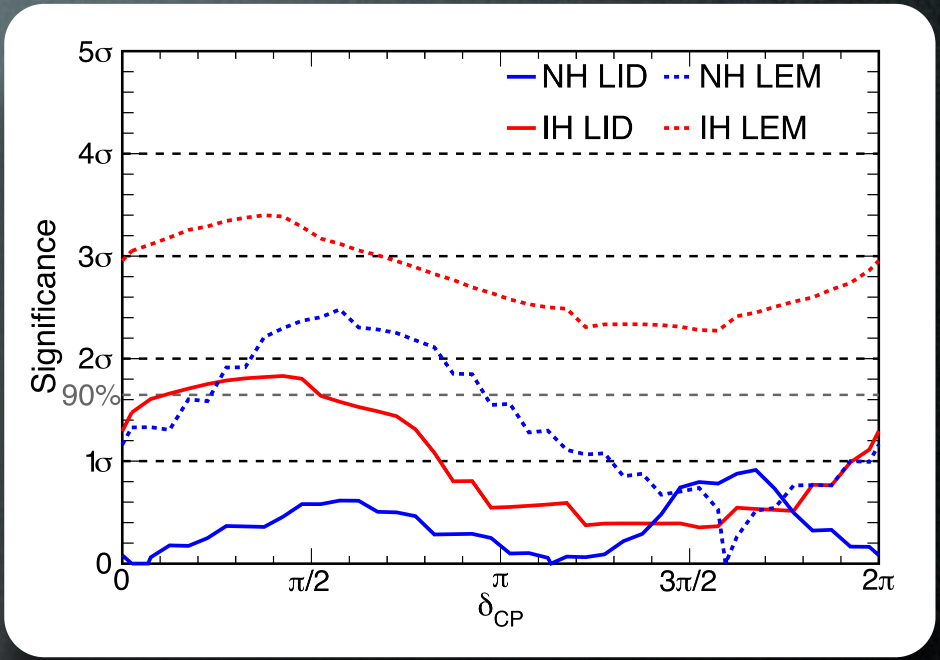
- The next generation experiments will require percent-level uncertainties to reach design sensitivities
- For current Hyper-K project, the largest uncertainties are from $\sigma(\nu_e)/\sigma(\nu_\mu)$ and multi-nucleon interactions (more on these later)

The Current Generation

T2K



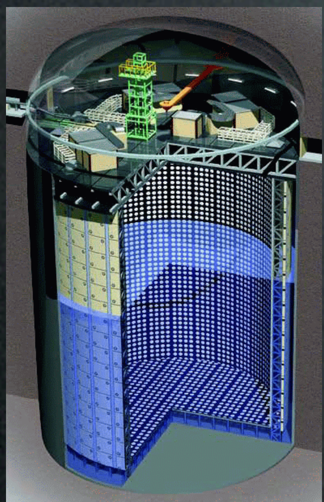
NOνA



- Existing experiments see an excess of $\nu_\mu \to \nu_e$ events relative to the δ_{CP} = 0 prediction
    - Current data indicates that δ_{CP} may be close to -π/2
- If that is true, the first evidence (i.e. 3σ) of CP violation may be possible prior to Hyper-K and DUNE
    - Both T2K and NOνA are now considering additional data taking

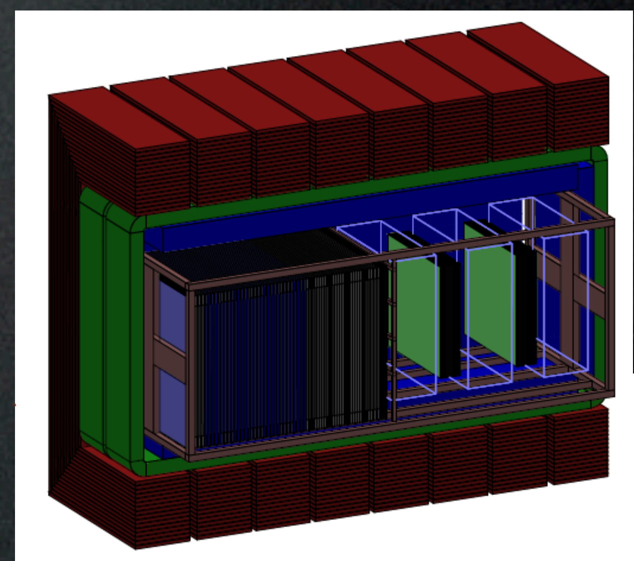
The T2K Experiment

Super-K Detector



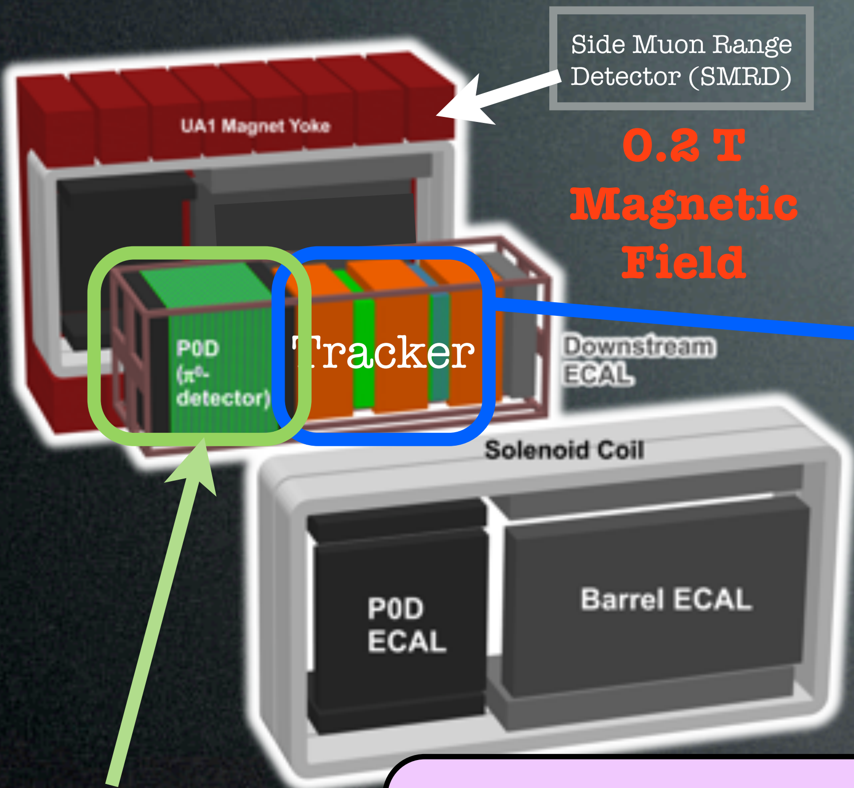
J-PARC Accelerator

Near Detector

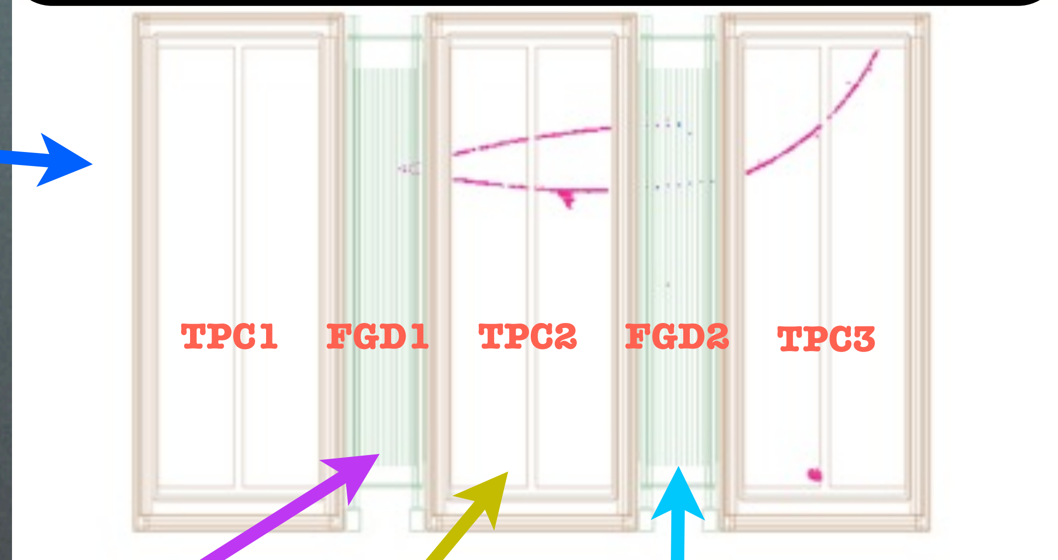


- The T2K experiment searches for neutrino oscillations in a **high purity ν_μ beam**
- A **near detector** located 280 m downstream of the target measures the **unoscillated neutrino spectrum**
- The **neutrinos travel 295 km** to the Super-Kamiokande water Cherenkov detector
    - Search for **appearance of ν_e** (to measure θ_{13}, δ_{CP})
    - Search for **disappearance of ν_μ** (to measure θ_{23}, Δm^2_{31})

T2K Near Detector (ND280)



CC Interaction in the Tracker



π^0 Detector (P0D)

- Scintillator strips with brass to convert photons
- Measure π^0 production

Fine-Grained Detectors (FGDs)

- Scintillator strips
- Provides neutrino target
- Detailed vertex information

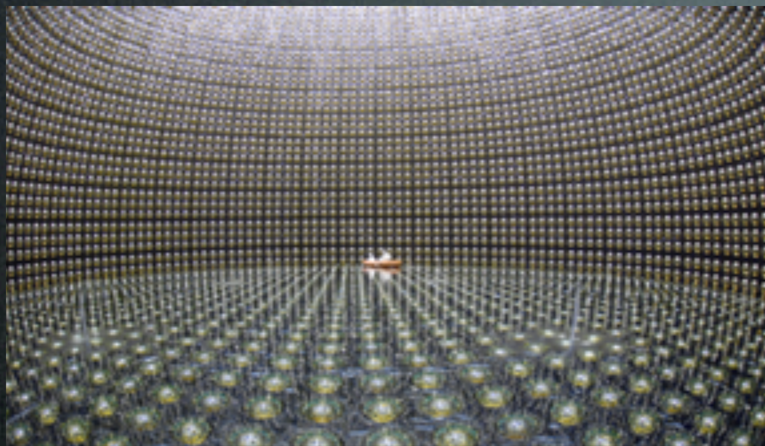
Time Projection Chambers (TPCs)

- Gas ionization chambers
- Momentum from curvature
- Particle ID from dE/dx

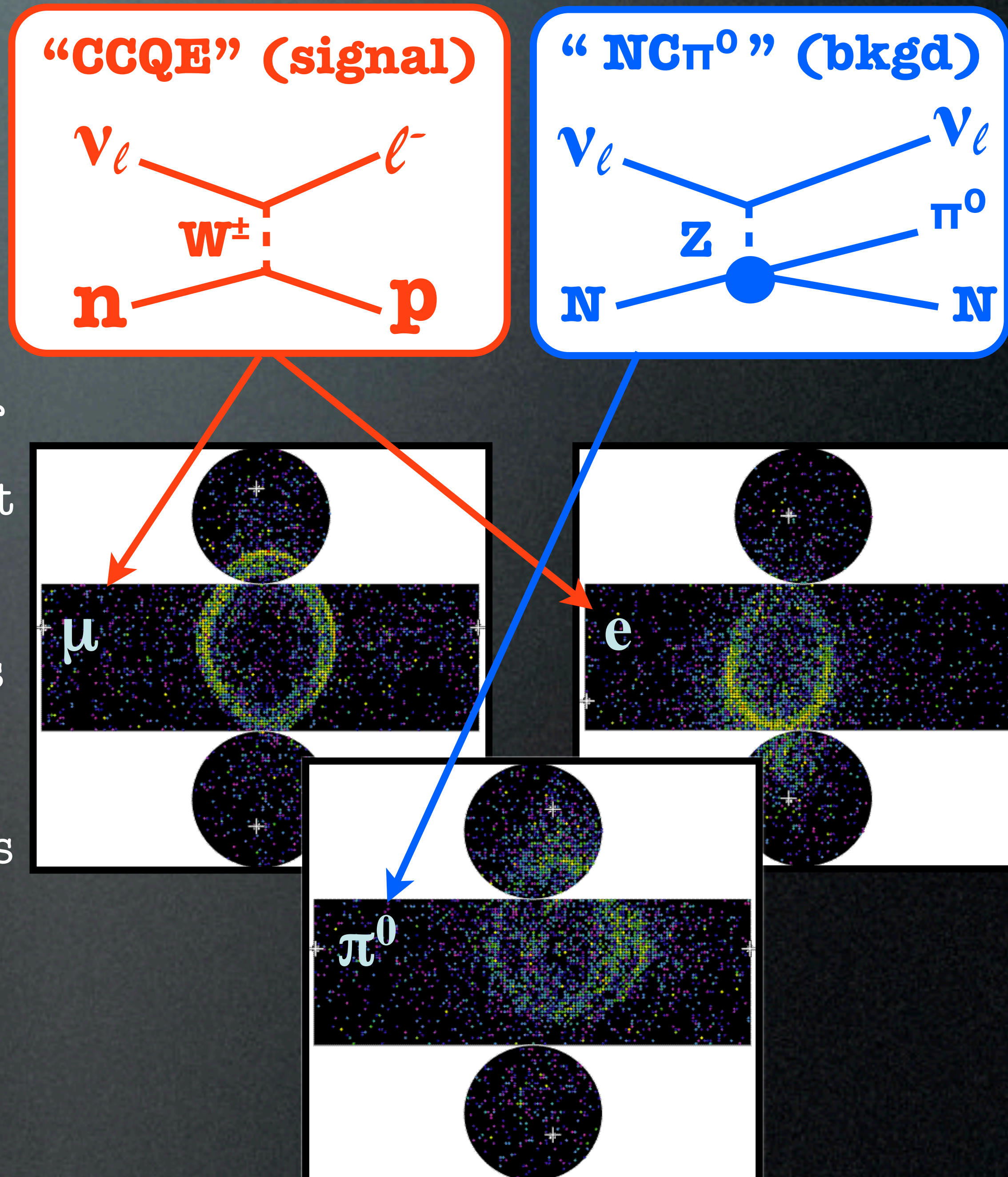
FGD2 has water layers to constrain interactions on the same target as Super-K

Newly incorporated for 2016 analysis

Water Cherenkov Particle ID

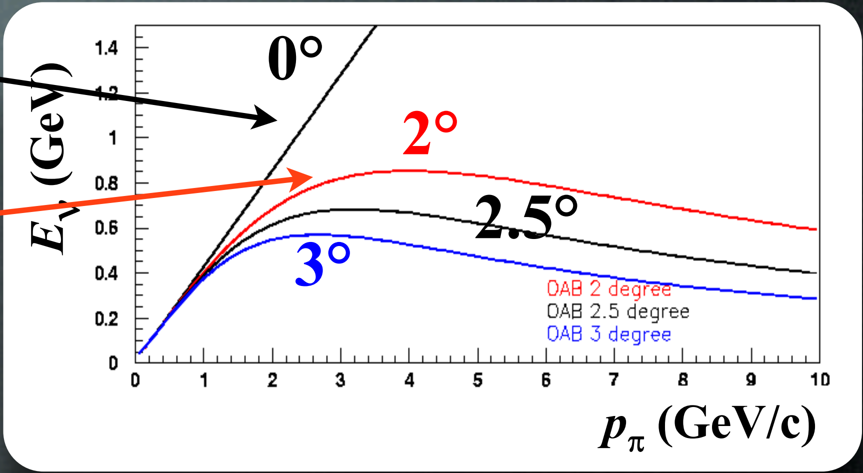


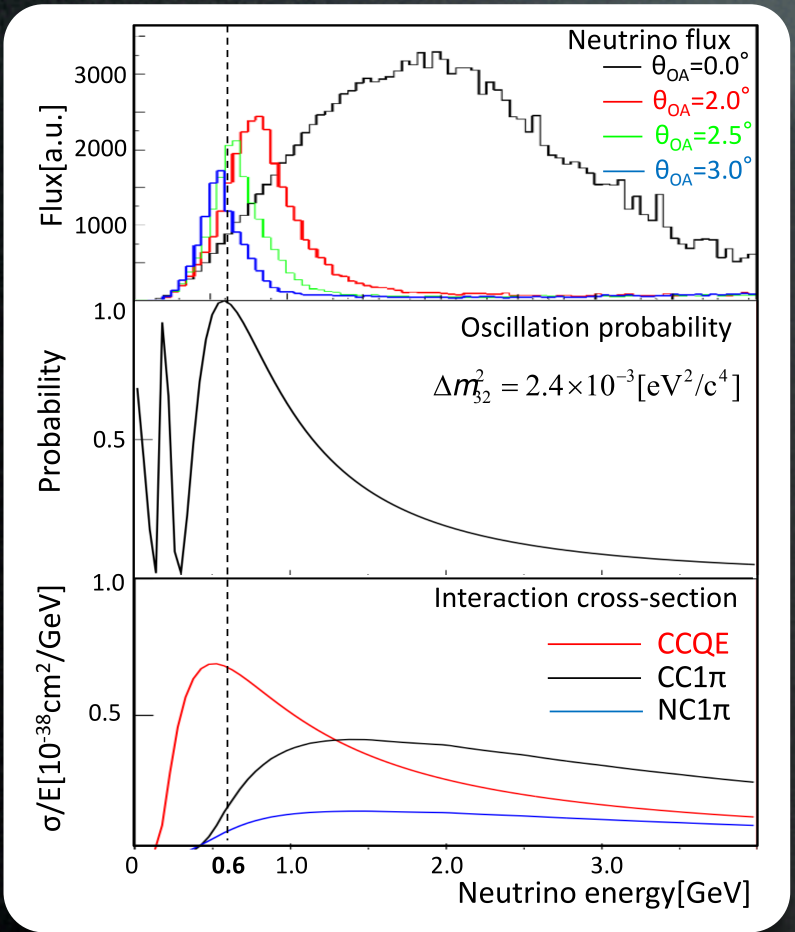
- 50 kton water Cherenkov detector
  - 39.3m diameter, 41.4m height
- **$\nu_\mu \rightarrow \mu^\pm$ detection**
  - Less scattering $\Rightarrow$ sharp rings
- **$\nu_e \rightarrow e^\pm$ detection**
  - More scattering $\Rightarrow$ fuzzy rings
- **ν_e background $\rightarrow \pi^0$**
  - 2 electron rings ($\pi^0 \rightarrow 2\gamma$)
  - To separate from electrons, **MUST** detect 2nd ring



Off-Axis Neutrino Flux

- Along the beam direction, **$E_\nu \propto p_\pi$**
- By pointing the beam slightly off-axis, **$E\nu \approx$ constant** (above some p_π)

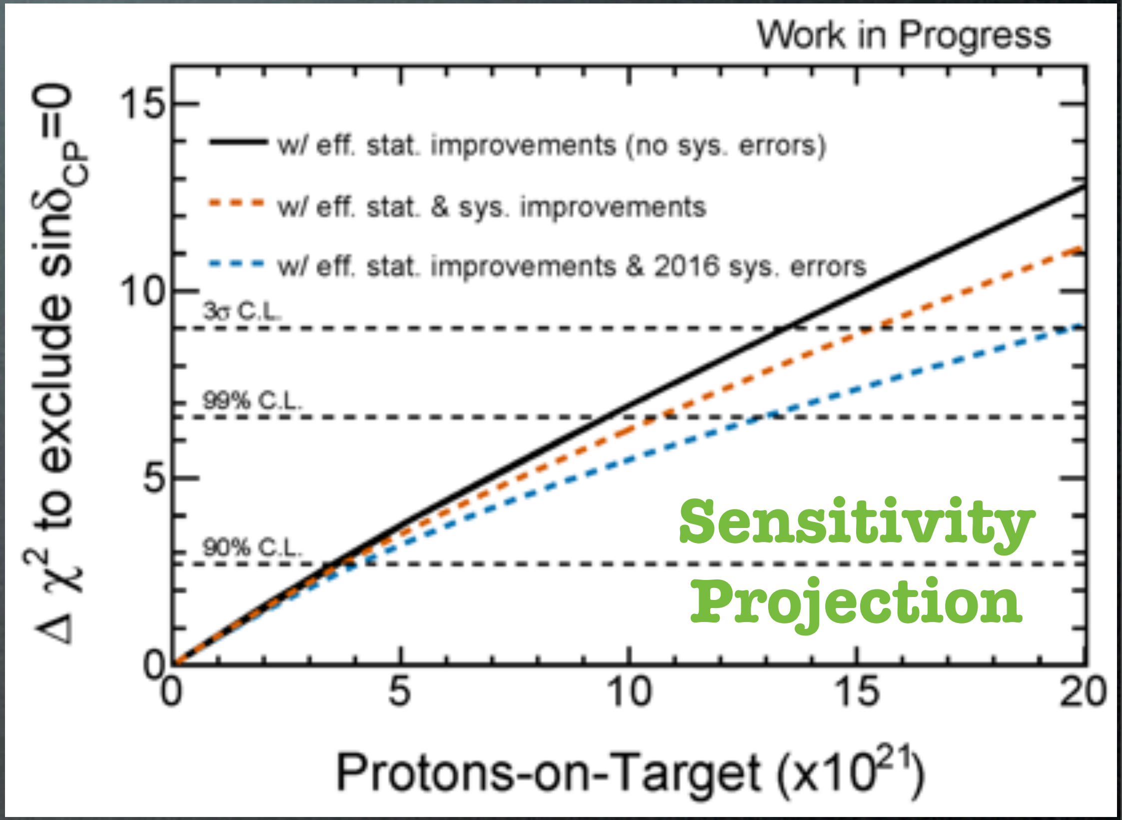




- Can **tune ν energy peak** by varying the off-axis angle
  - Optimize for oscillation maximum
- Reduces the high E_ν tail
  - Reduces the $NC\pi^0$ background
  - Reduces the CC-multi-π and DIS backgrounds
- **This off-axis effect is the key physics principle exploited by NuPRISM**

T2K Extended Run

- With 20 x 10^{21} POT, T2K can achieve 3σ CPV sensitivity if:
  - 50% increase in ν_e efficiency
    - Multi-ring event samples + larger fiducial volume
  - Current systematic errors do not get larger
  - $\delta_{CP} = -\pi/2$
- A reduction of the 2016 systematic errors by 33% is equivalent to 33% more POT
- Systematic errors will have a large impact on the sensitivity



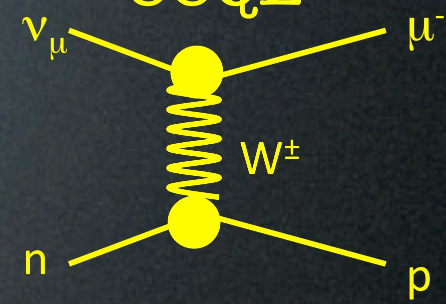
Why is it so Difficult to Reach 2-3% Systematics?

Neutrino-Nucleus Interactions

Neutrino Interactions

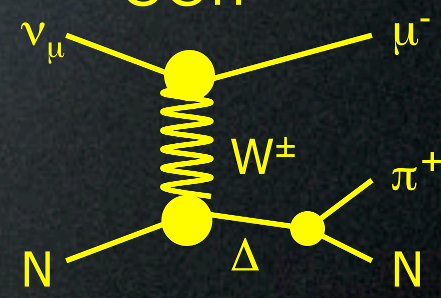
(Circa 2009)

CCQE

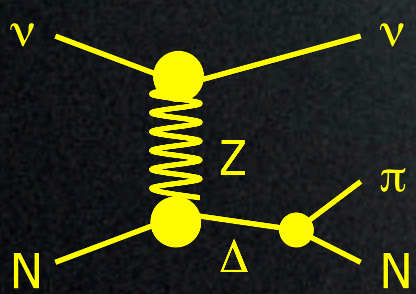


- Charged Current Quasi-Elastic (CCQE)
  - Neutrino flavor is tagged by outgoing lepton
  - Often the signal mode for oscillation experiments
- Charged Current Pion Production ($CC\pi^+$)
  - Comparable cross section to CCQE at 1 GeV
  - Background to CCQE-based oscillation searches

$CC\pi^+$



NCπ

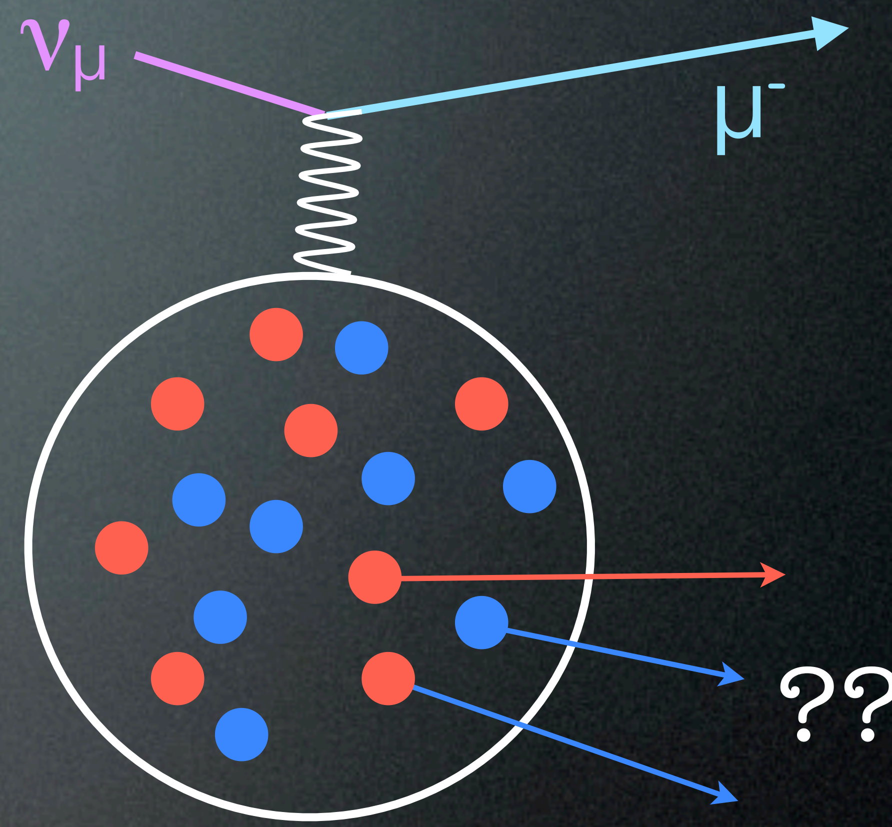


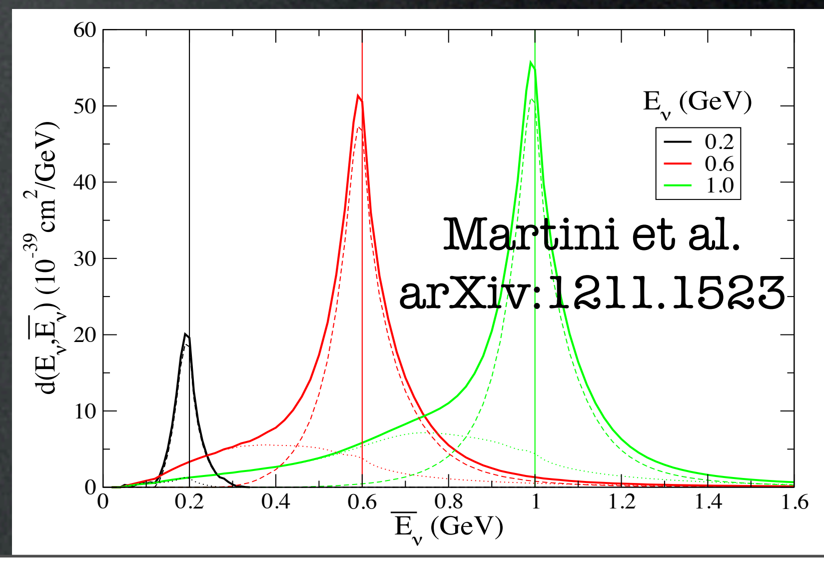
- Neutral Current Pion Production (NCπ)
  - $NC\pi^0$ produces 2 photons
    - Can be misidentified as an electron
  - $NC\pi^+$ produces a single charged track
    - Can be misidentified as either a muon or electron
- Deep Inelastic Scattering (DIS) turns on around 2 GeV

Each of these interactions have only a few free parameters, so detectors were designed to simply constrain those parameters

Nuclear Complications

- Unfortunately, neutrino-nucleus scattering is not as simple as single-nucleon knockout
  - Quite often (20-30%?), more than 1 nucleon is ejected from the nucleus
- This affects both the reconstructed energy and the total cross section of single-lepton events
  - In 2009, our neutrino interaction generators were unaware of this effect

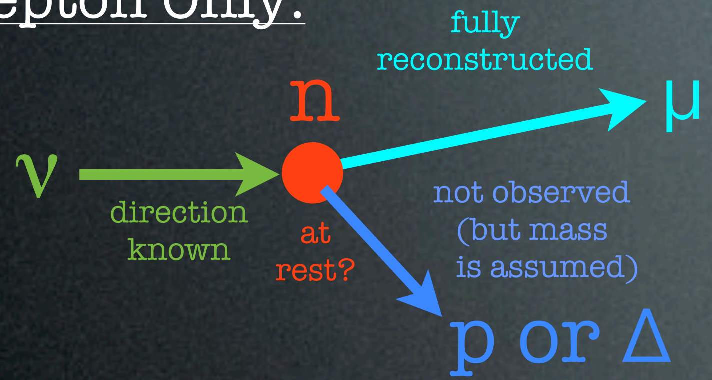




Measuring E_ν

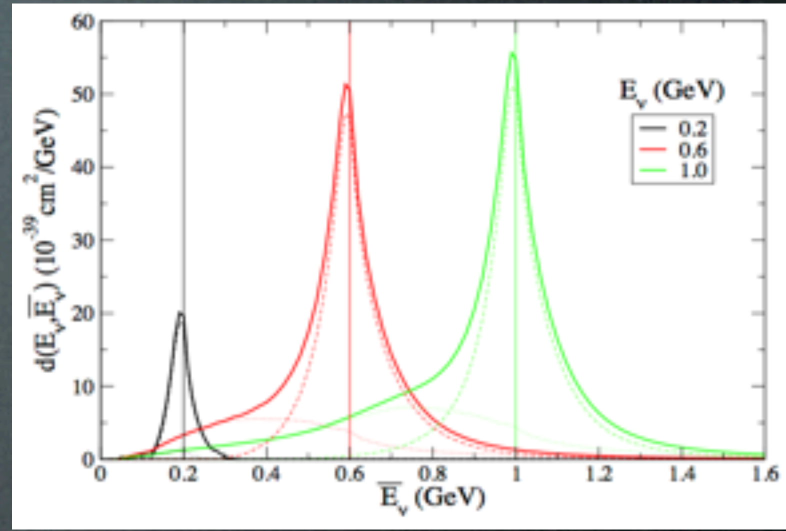
Martini et al. arXiv: 1211.1523

Lepton Only:



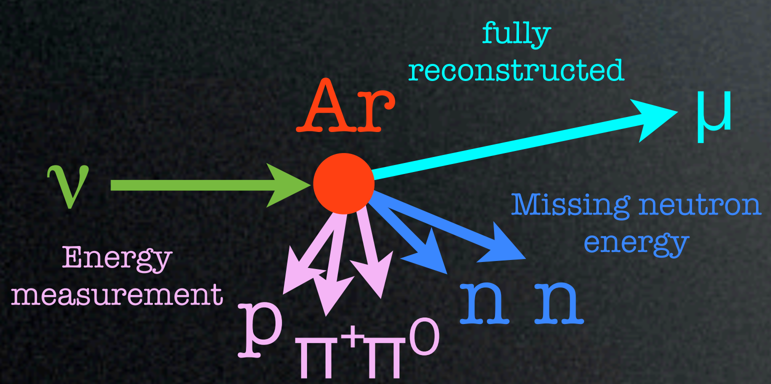
Must assume mass of recoiling hadron(s)

Problematic! due to Multi-nucleon interactions



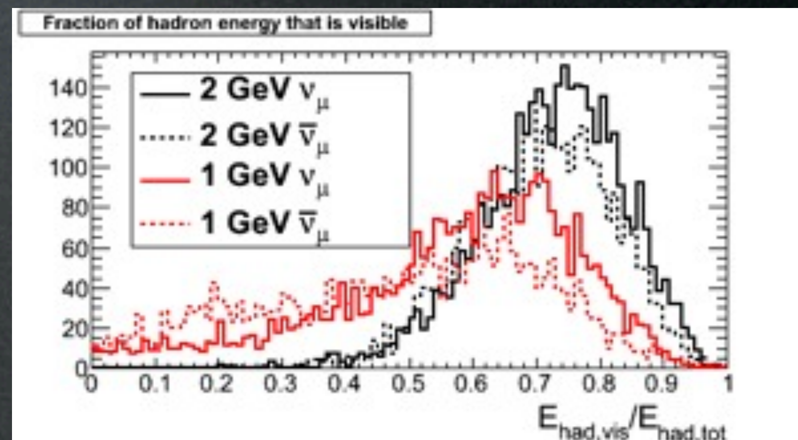
Lepton + Hadronic Energy:

http://public.lanl.gov/friedland/LBNEApril2014/LBNEApril2014talks/McGrew_LANL_Apr2014.pdf



Neutrons cause missing hadronic energy

Energy loss is different for ν and anti-ν



GEANT4 Simulation of a large LAr volume

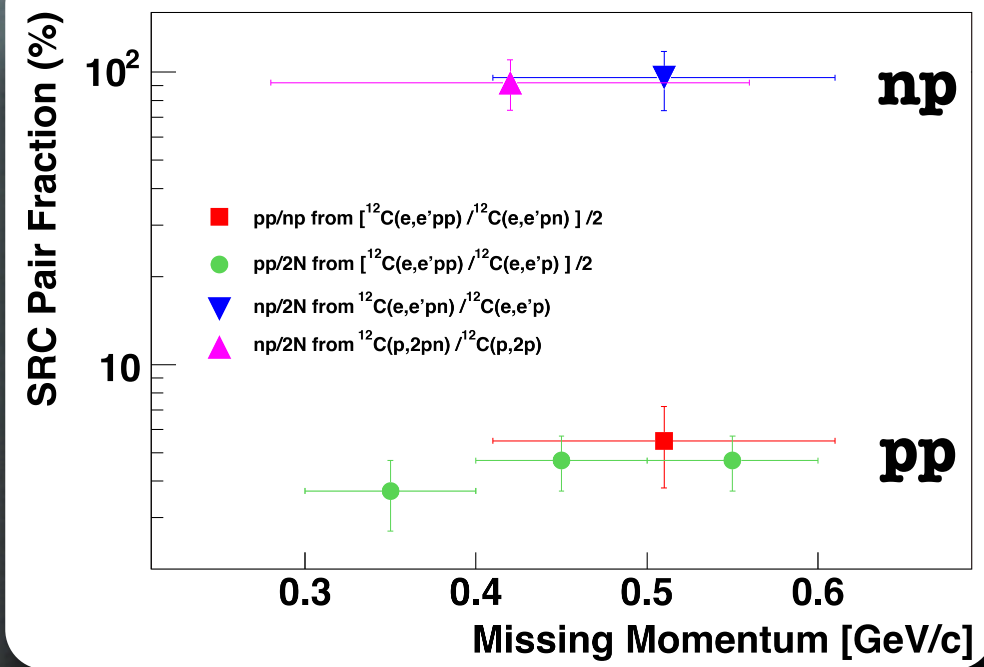
(True deposited hadronic energy)/
(True initial hadronic energy)

- Both effects lead to underestimating the neutrino energy (feed down)
- Need to calibrate both leptonic (e & μ) & hadronic energy scales and energy tails (variance)

Correlated Nucleons

- The electron scattering community has long known about multi-nucleon interactions
  - Nucleons are often found in pairs due to:
    - Long-range correlations (LRC; >fm)
    - Short-Range Correlations (SRC)
- Electron scattering shows a much **higher rate** of **np** pairs relative to **pp** or **nn** pairs
  - This can have large implications for calorimetric energy measurements
    - Implies differences between neutrinos (np->pp) and anti-neutrinos (np->nn)
- How can we understand this effect in neutrino interactions?
  - Axial-vector coupling
  - Distributed throughout the nucleus
  - ...

np and pp Pairs in Electron Scattering



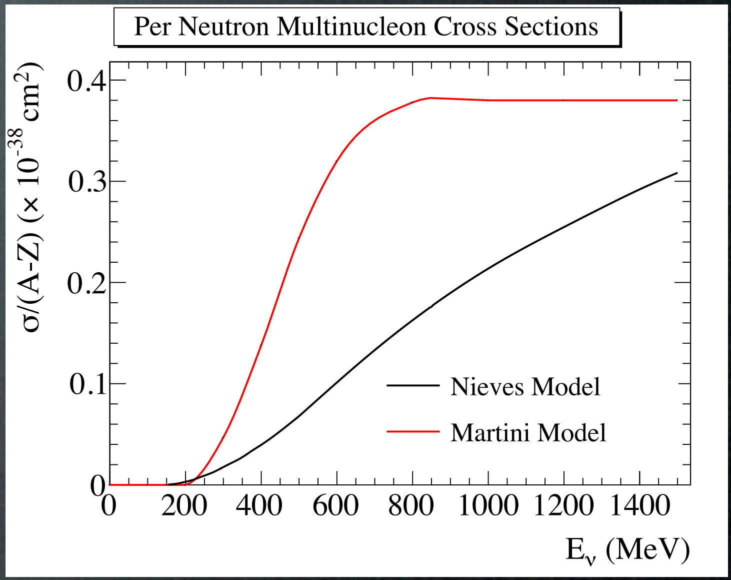
4.627 GeV electrons with 19.5° scattering angle

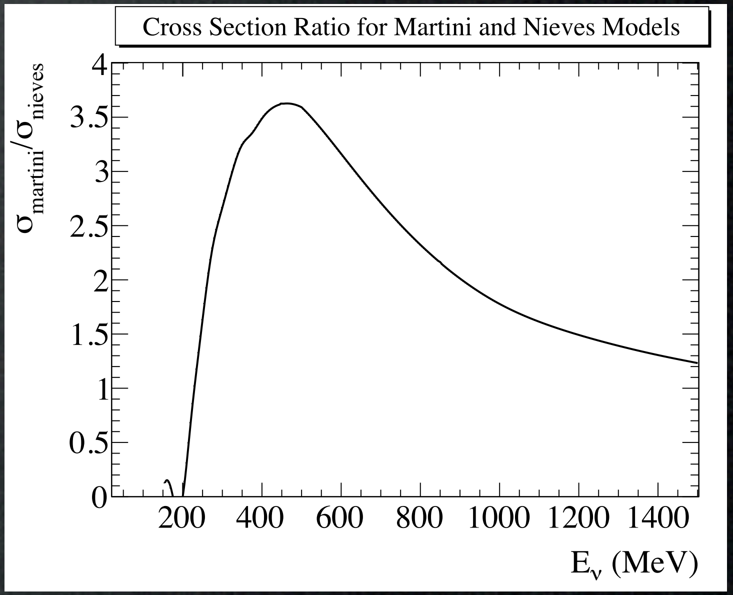
Protons measured at 3 different scattering angles

R. Subedi et al., Science 320, 1476 (2008)

How Well are Multinucleon Models Understood?

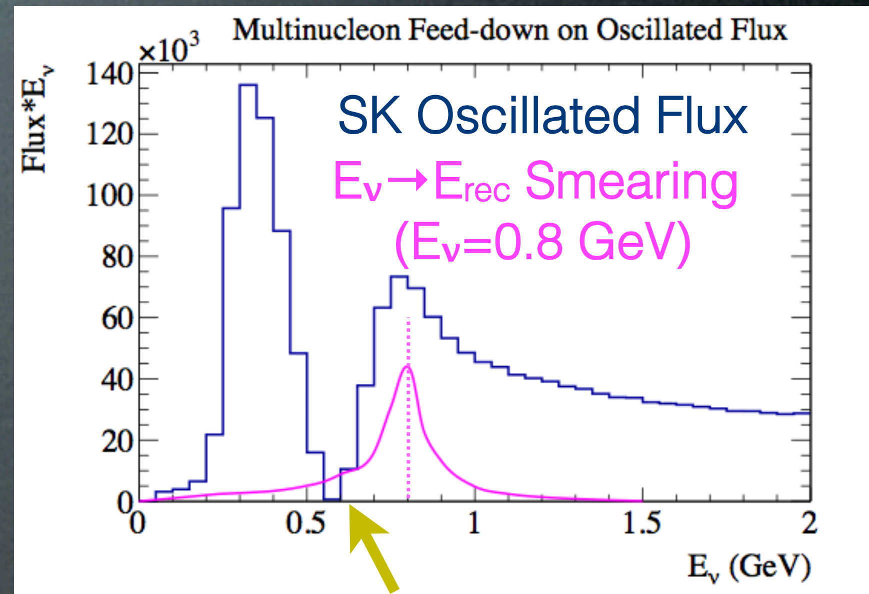
- It is very difficult to answer this question without a direct measurement
- However, the two most commonly used "new" models can be compared
  - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
  - M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80:065501 (2009)
- Cross section differs by a factor of 2 to 3 over a large range of neutrino energies
- Which model is correct?
  - Is either model correct?
- 1 GeV is a particularly difficult regime for nuclear theory





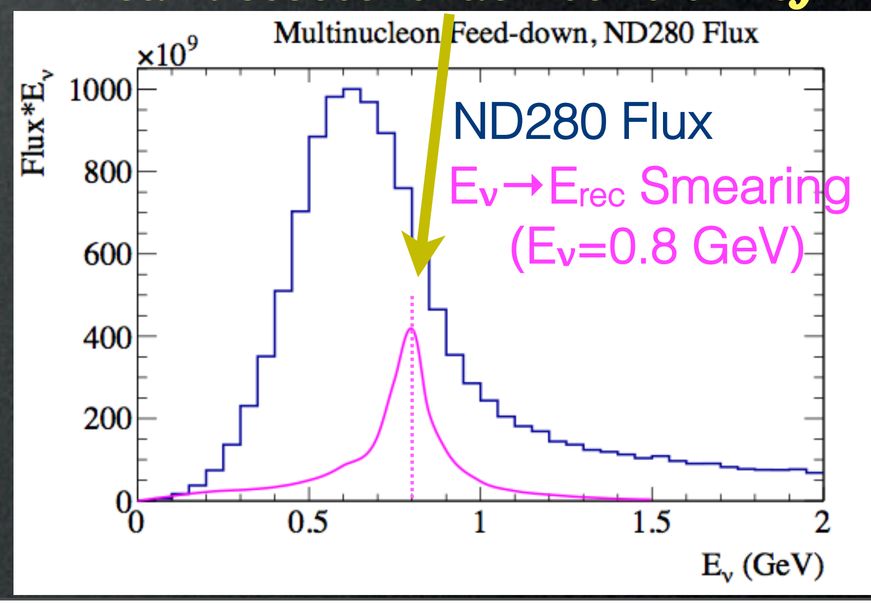
Constraints from Typical Near Detectors

- Shouldn't cross section systematics cancel in a near/far fit?
  - Some errors, like total normalization, will cancel
- However, multi-nucleon and pion absorption events feed-down into oscillation dip
  - Cannot disentangle with near detectors
    - Energy spectrum is not oscillated
- More multi-nucleon = smaller dip
  - **Multi-nucleon effects are largely degenerate with mixing angle effect!**



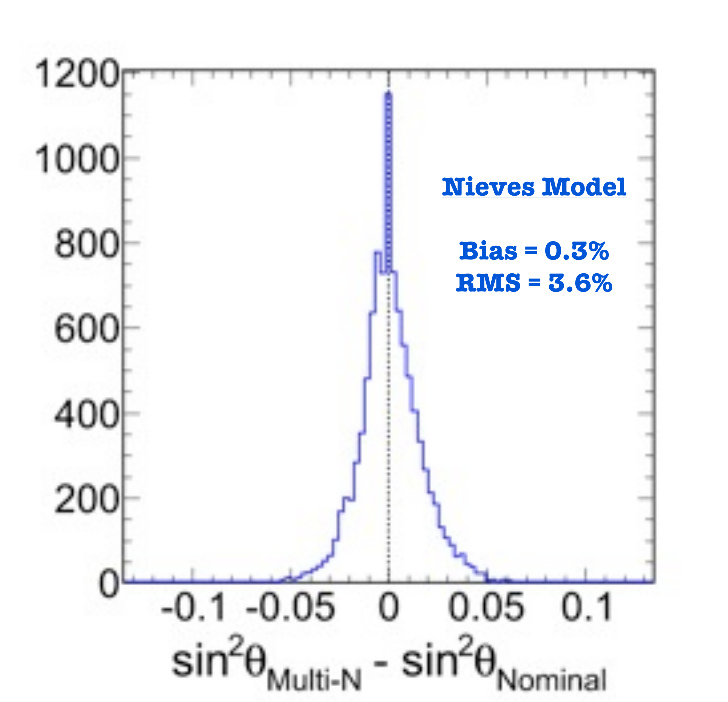
Mixing Angle Bias!

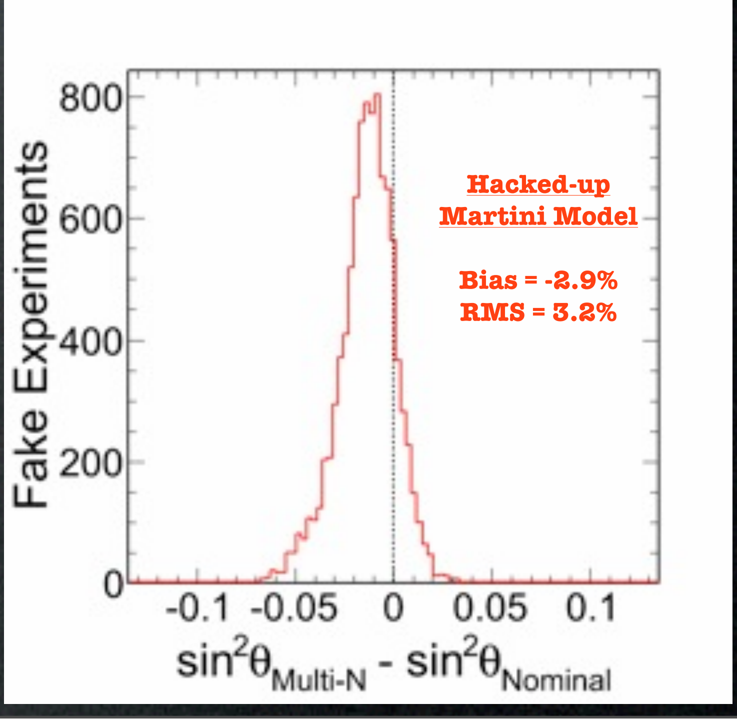
Near detectors lack sensitivity



Effect on T2K ν_μ Disappearance

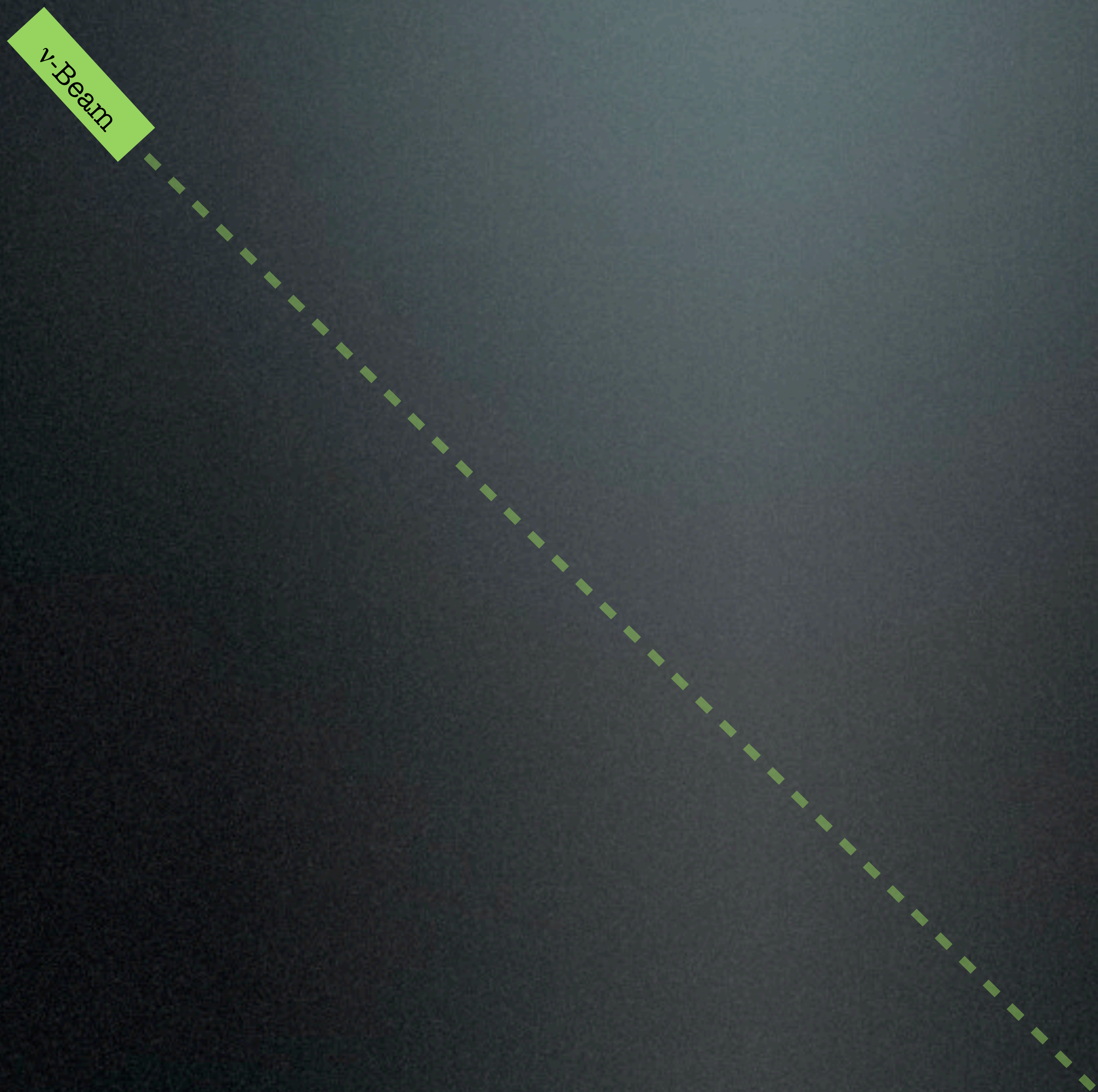
- Create "fake data" samples with flux and cross section variations
  - With and without multi-nucleon events
- For each fake data set, full T2K near/far oscillation fit is performed
  - For each variation, plot difference with and without multi-nucleon events
- For Nieves model, "average bias" (RMS) = **3.6%**
- For Martini model, mean bias = -2.9%, RMS = 3.2%
  - Full systematic = $\sqrt{(2.9\%^2+3.2\%^2)}$ = **4.3%**
  - **This is would be one of the largest systematic uncertainties for T2K**
- But this is just a comparison of 2 models
  - How much larger could the actual systematic uncertainty be?
- **A data-driven constraint is needed**





Can the E_ν problem be solved experimentally?

NuPRISM Detector Concept



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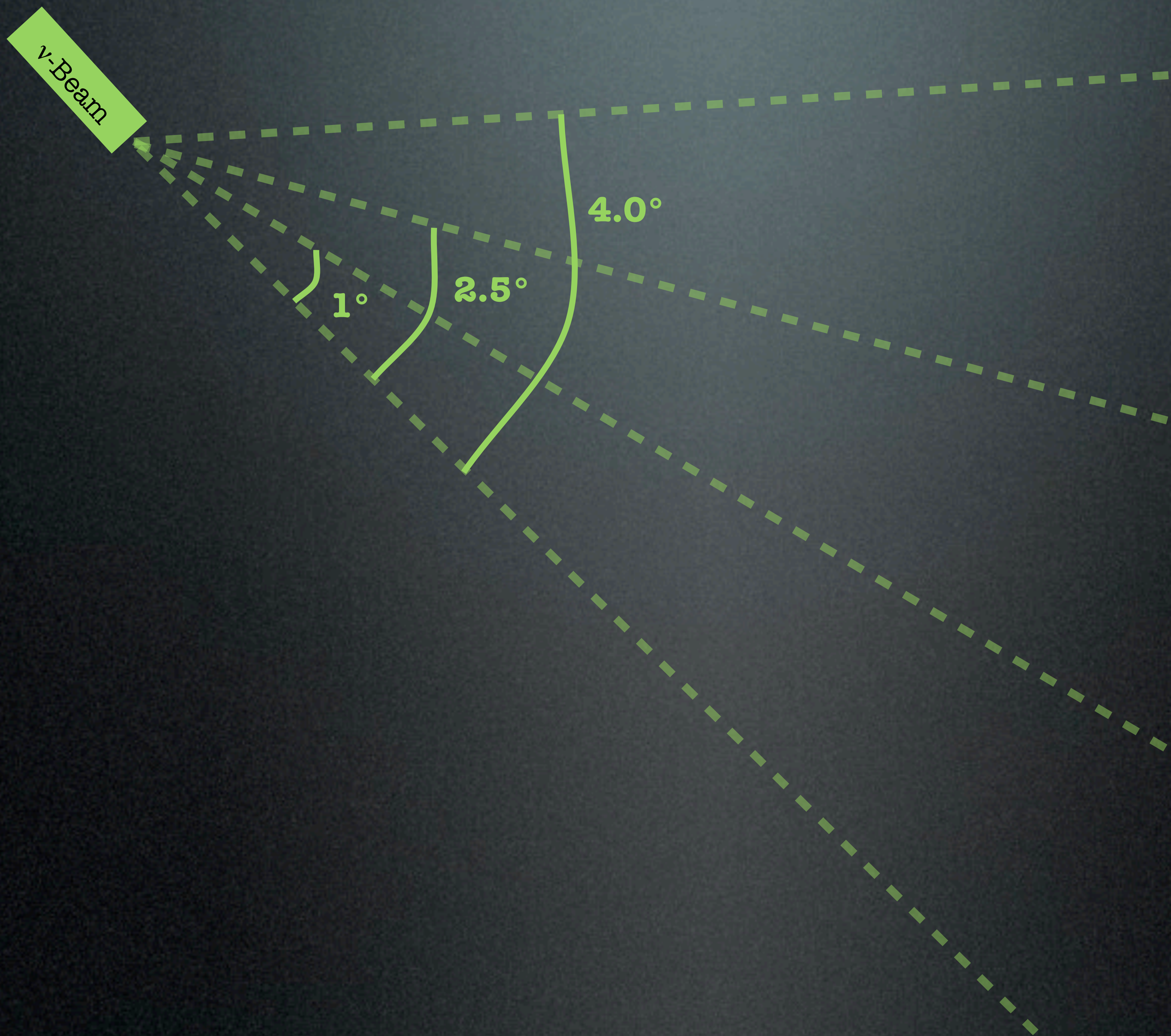

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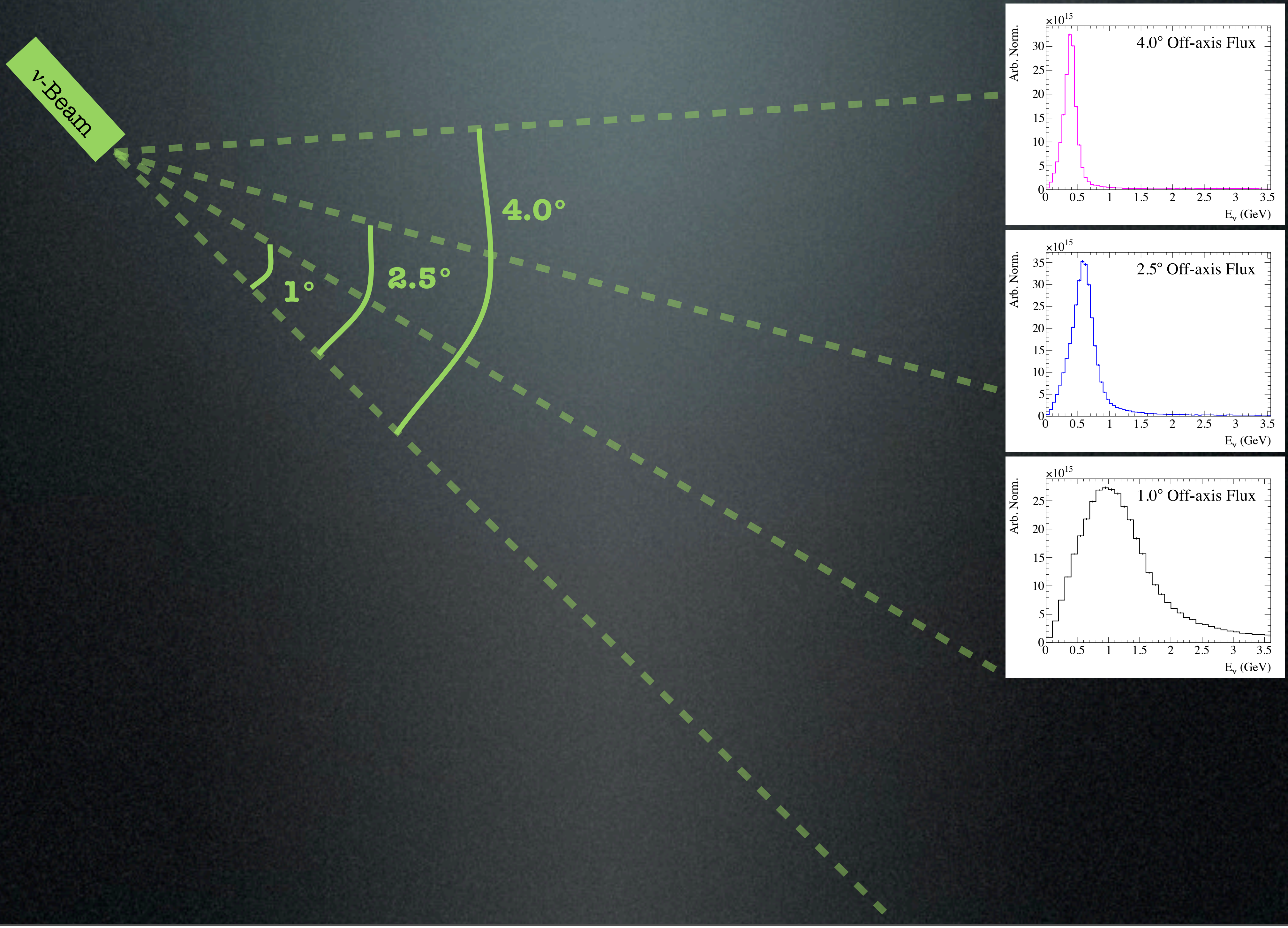

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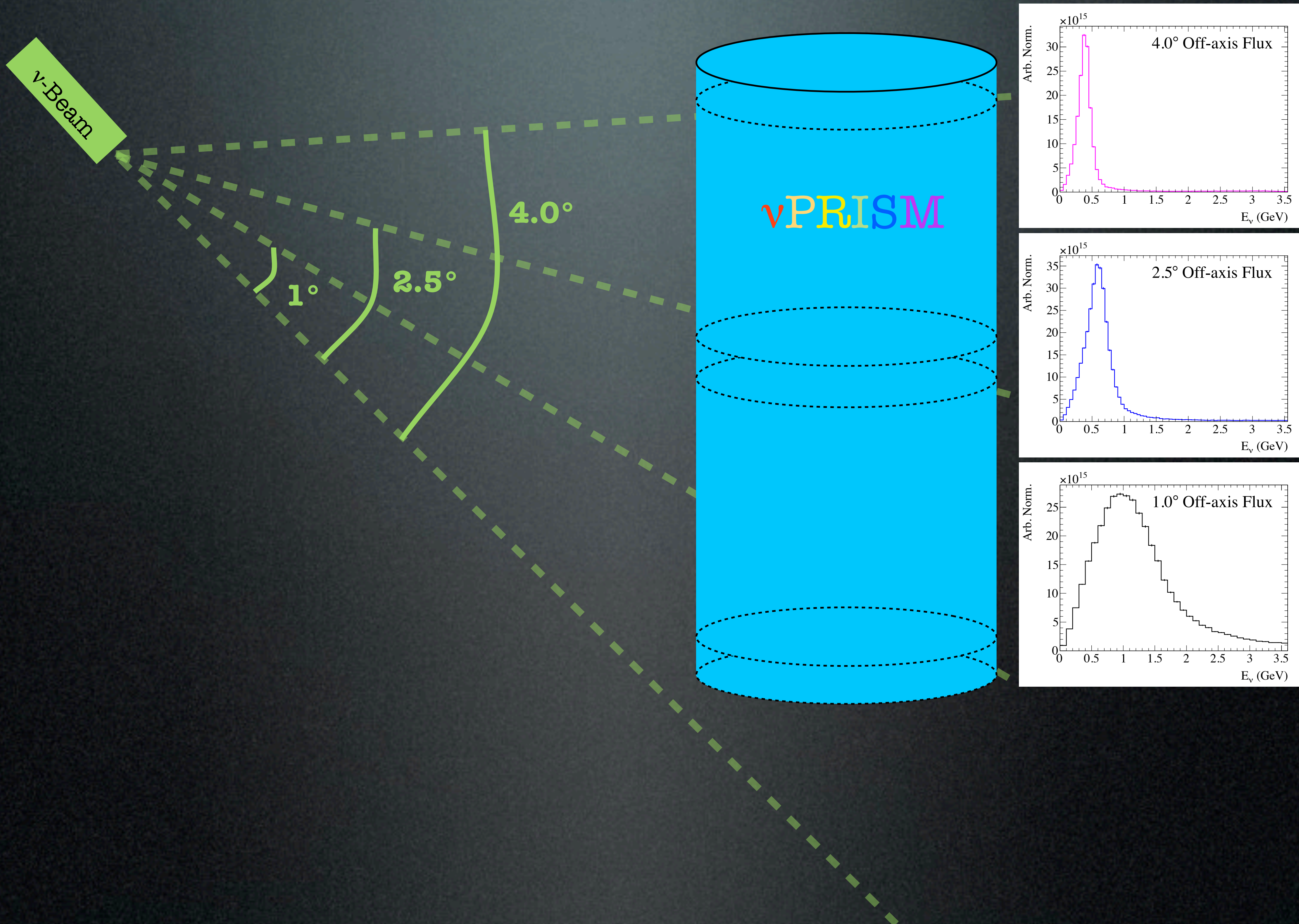

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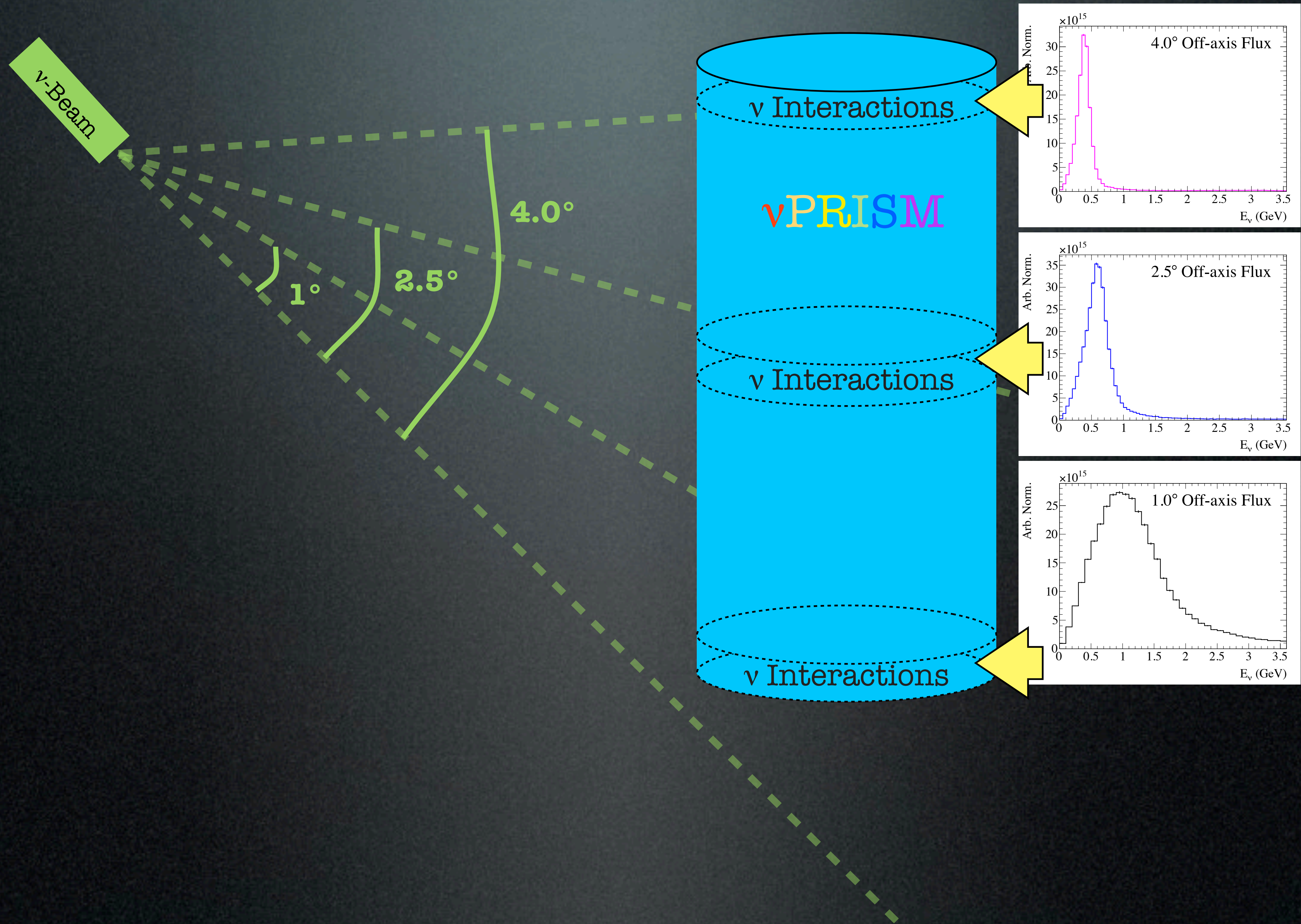

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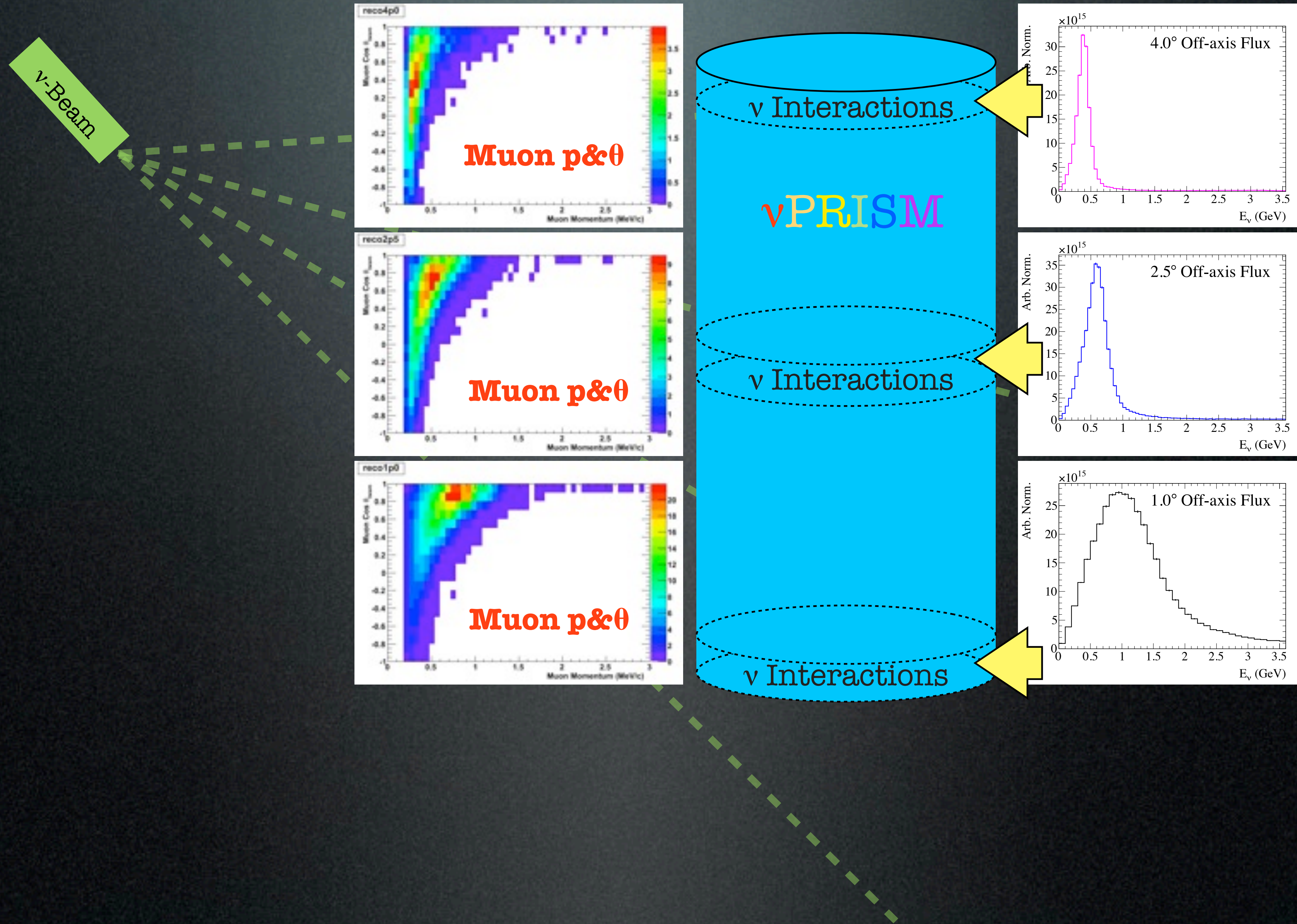

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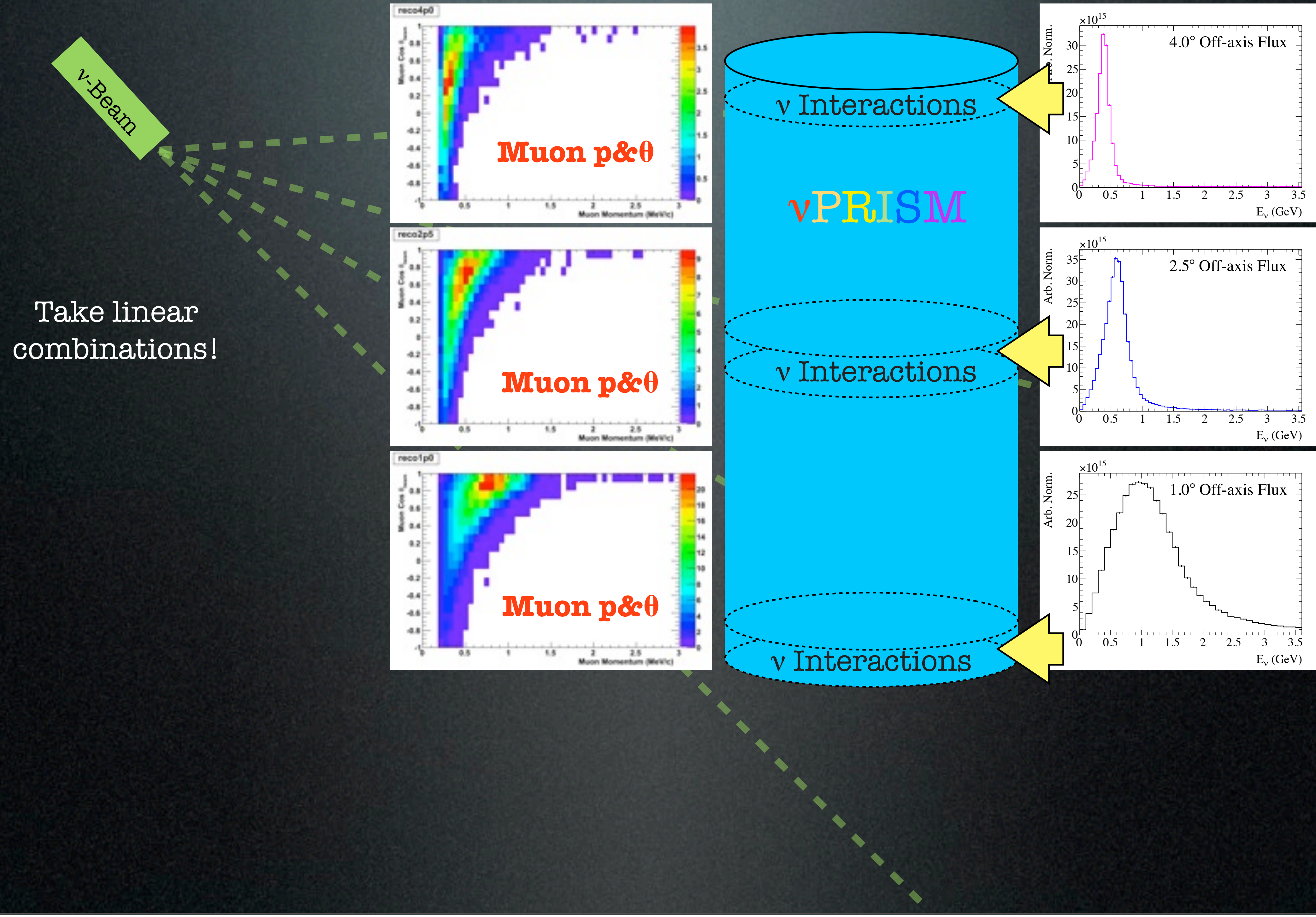

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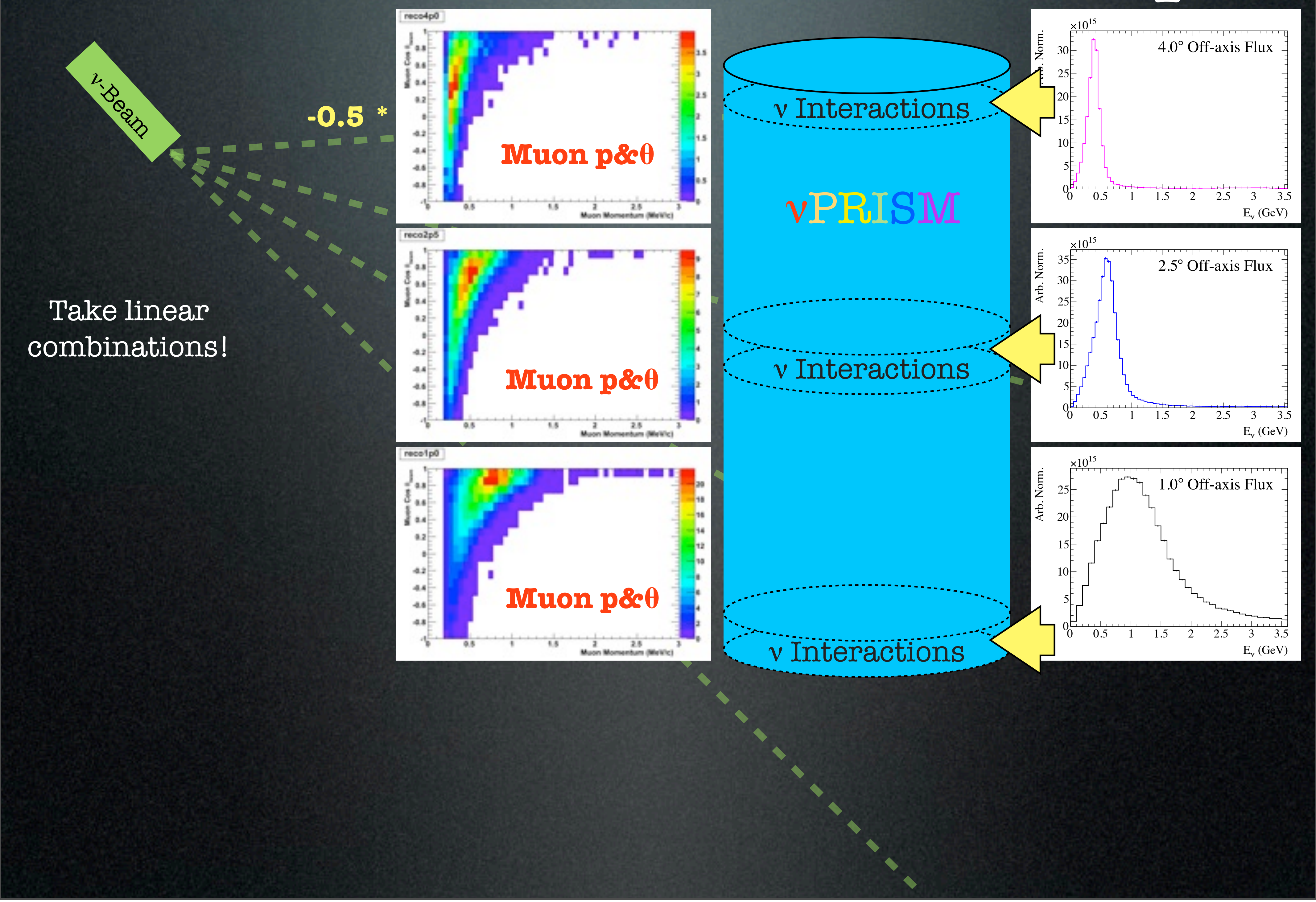

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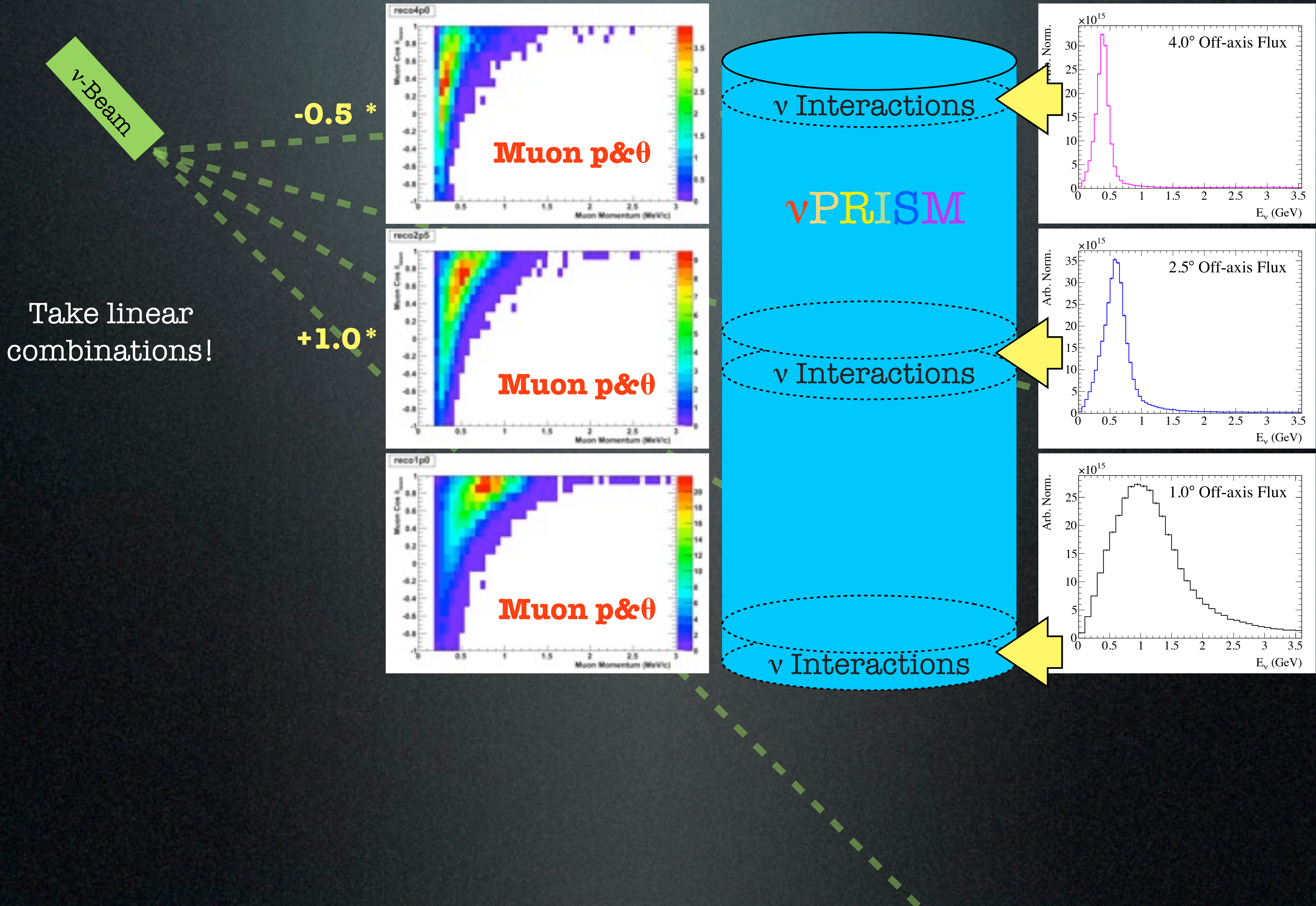

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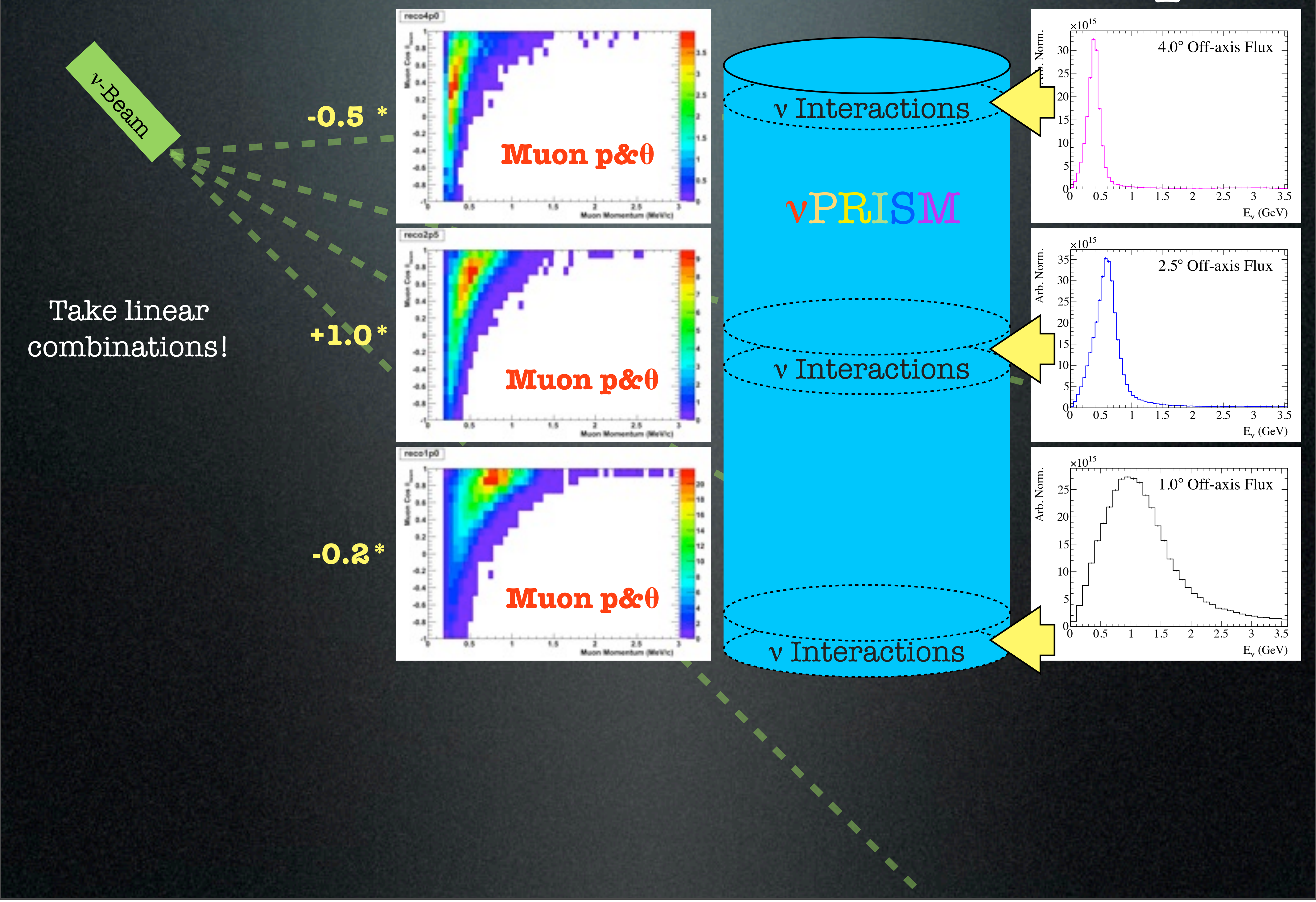

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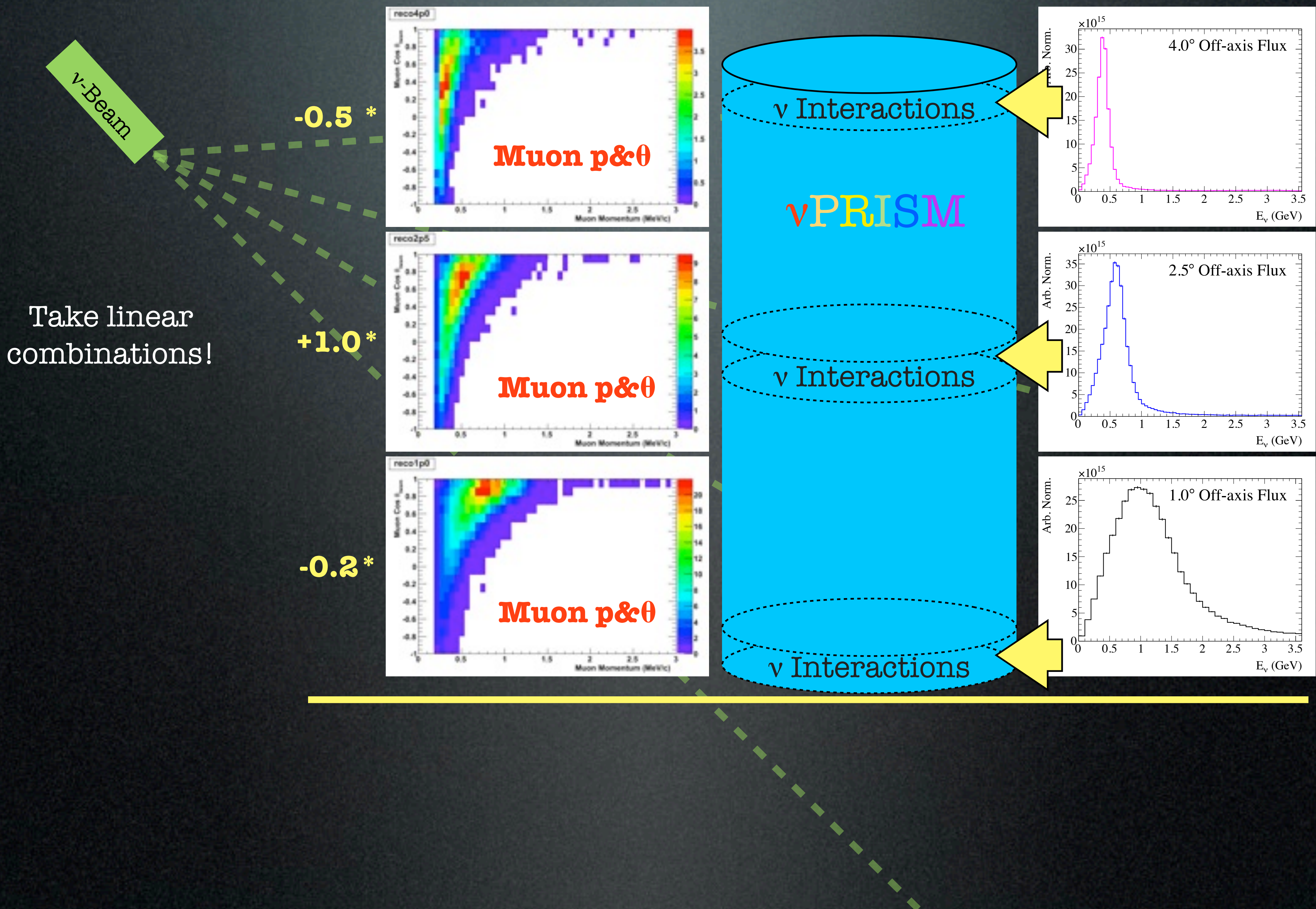

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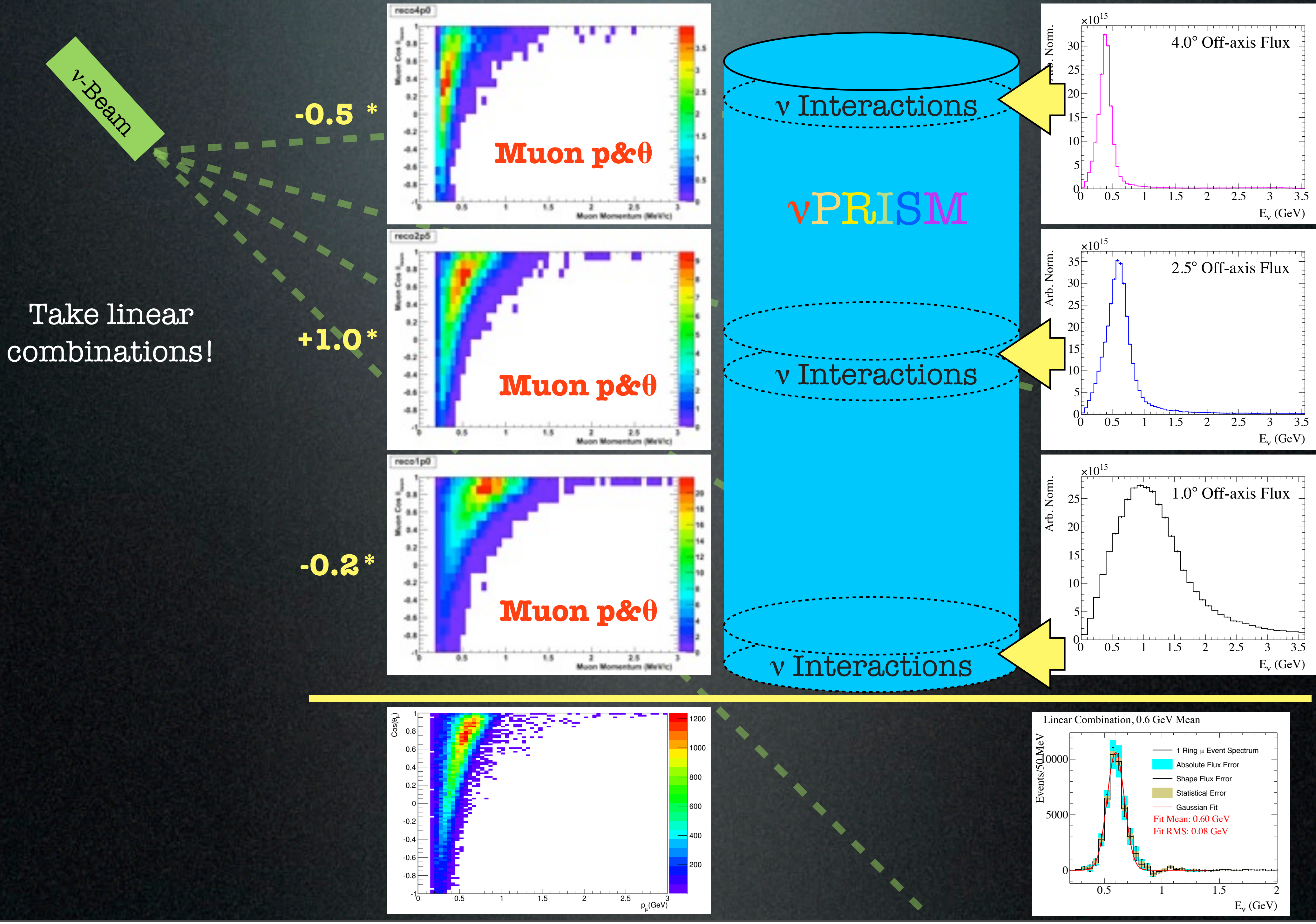
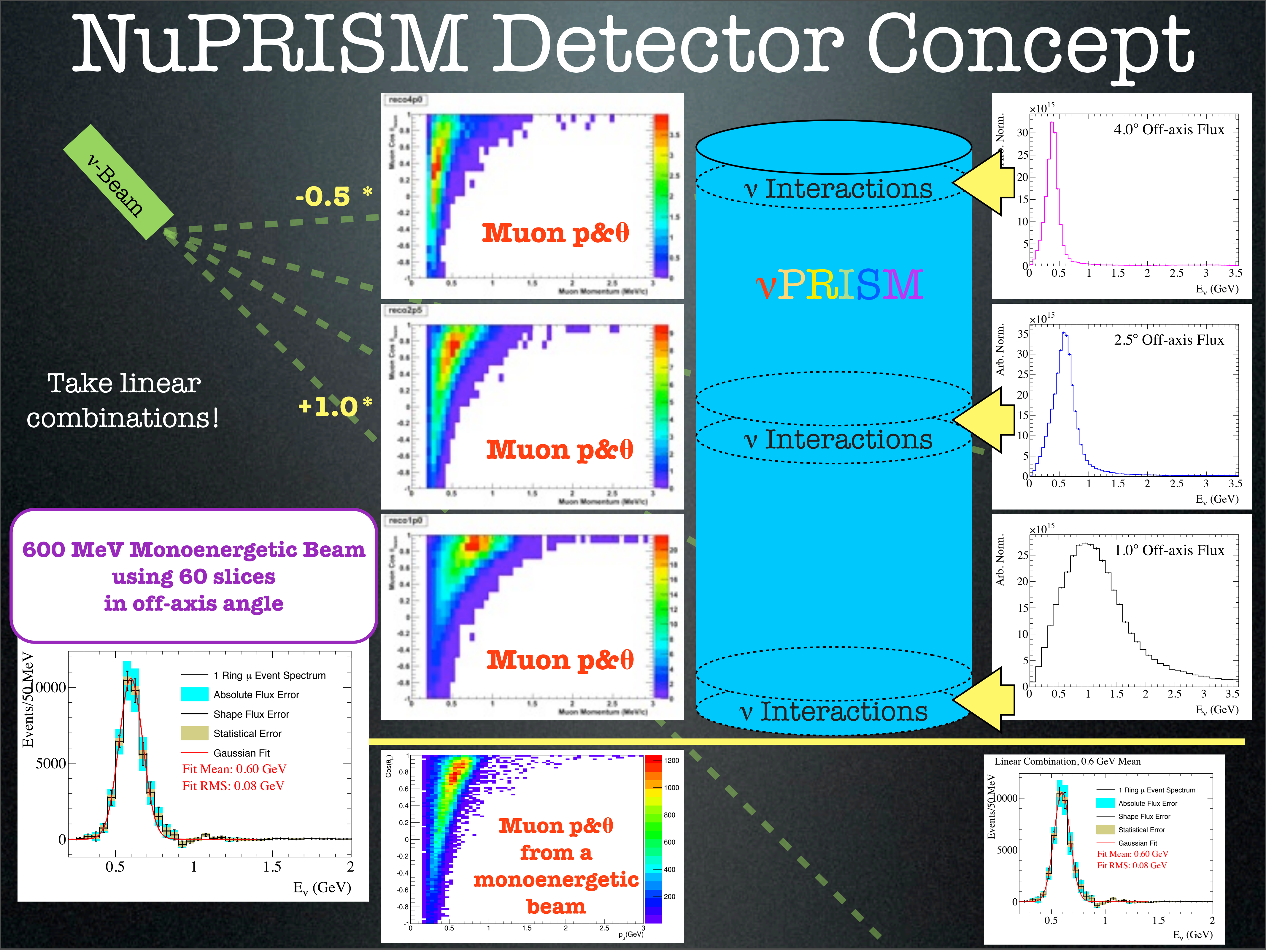
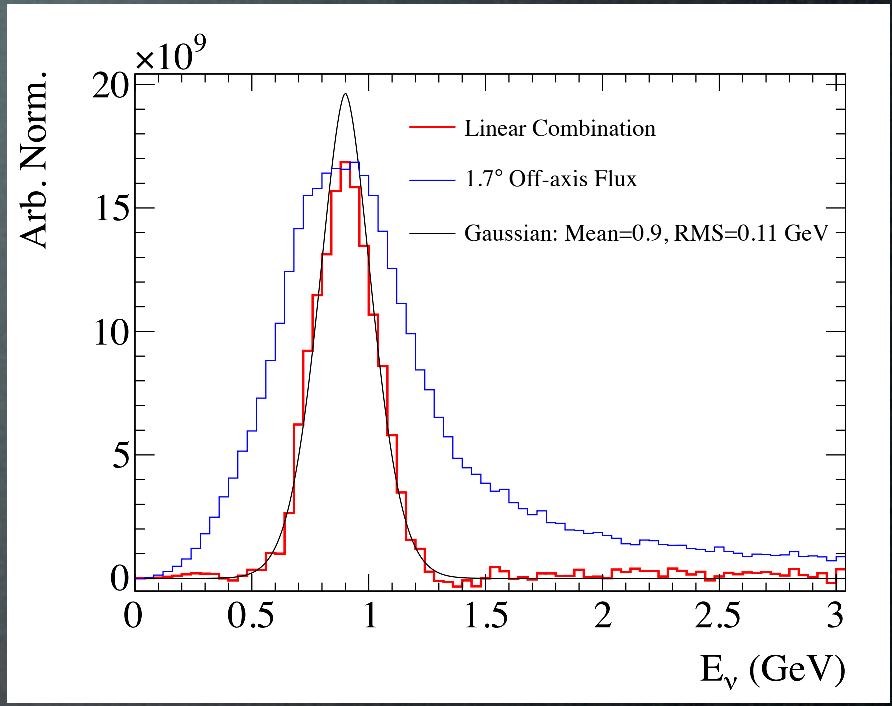
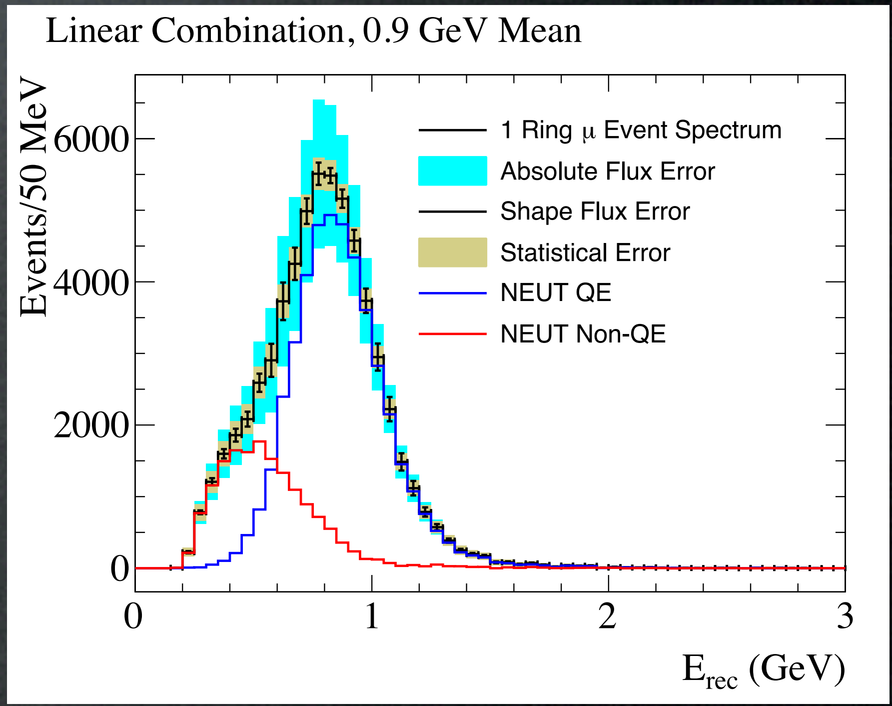



NuPRISM Detector Concept
ν-Beam
-0.5 *
+1.0 *
Take linear combinations!
600 MeV Monoenergetic Beam using 60 slices in off-axis angle
Muon p&θ
Muon p&θ
Muon p&θ
Muon p&θ from a monoenergetic beam
ν Interactions
νPRISM
ν Interactions
ν Interactions
4.0° Off-axis Flux
2.5° Off-axis Flux
1.0° Off-axis Flux
Arb. Norm.
E_ν (GeV)
Events/50 MeV
1 Ring μ Event Spectrum
Absolute Flux Error
Shape Flux Error
Statistical Error
Gaussian Fit
Fit Mean: 0.60 GeV
Fit RMS: 0.08 GeV
Linear Combination, 0.6 GeV Mean
Muon Momentum (MeV/c)
Muon Cos θ
Cos(θ_μ)
p_μ(GeV)

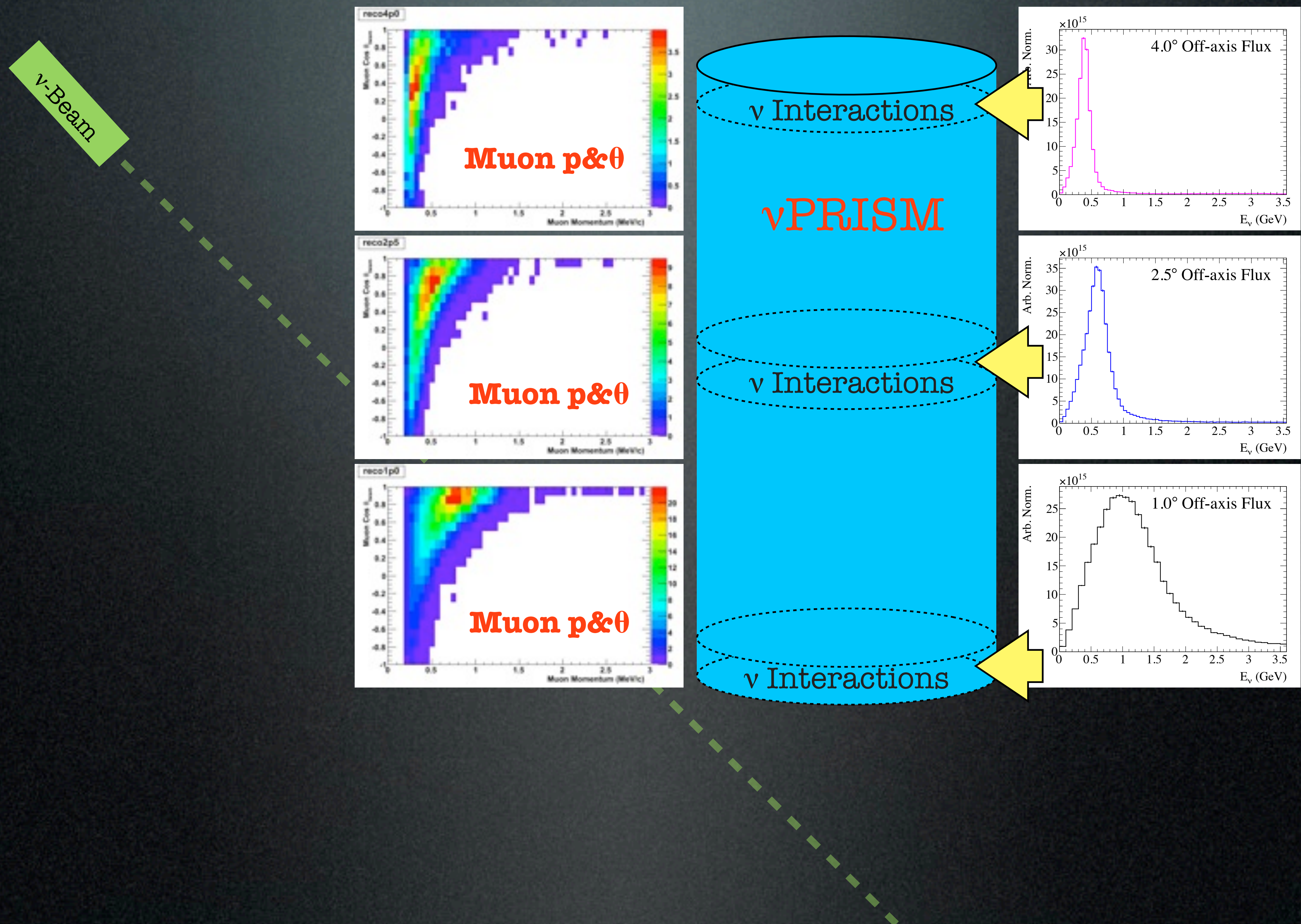
Benefits of a Monoenergetic Beam

- **Fully specified initial state!**
  - Electron-scattering-like measurements with neutrinos!
- First ever measurements of **$\sigma^{NC}(E_\nu)$**
  - Much better constraints on NC oscillation backgrounds
- First ever "**correct**" measurements of **$\sigma^{CC}(E_\nu)$**
  - No longer rely on final state particles to determine E_ν
- It is now possible to **separate the various components** of single-μ events!



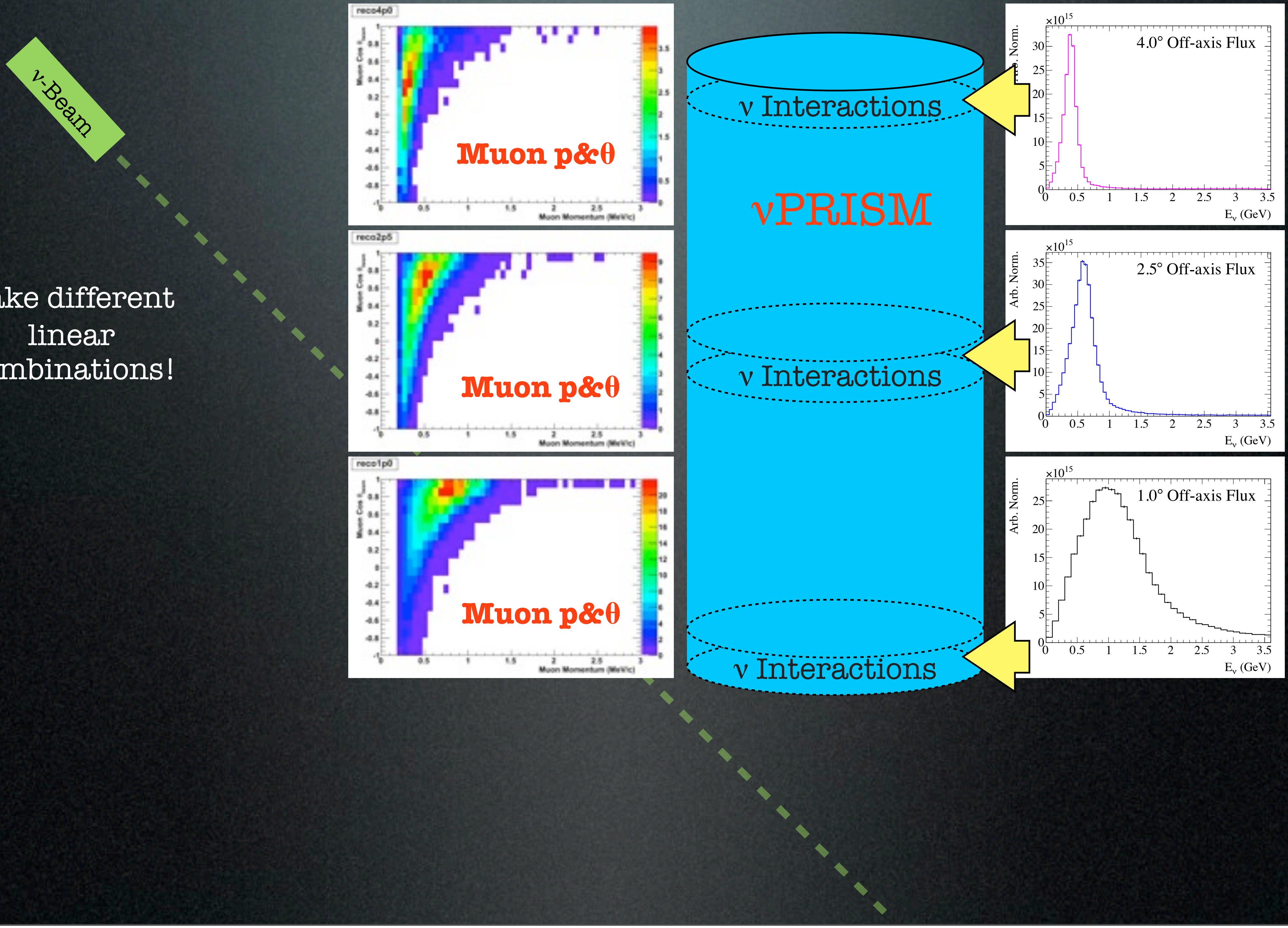


NuPRISM in Oscillation Experiments



NuPRISM in Oscillation Experiments

Take different linear combinations!



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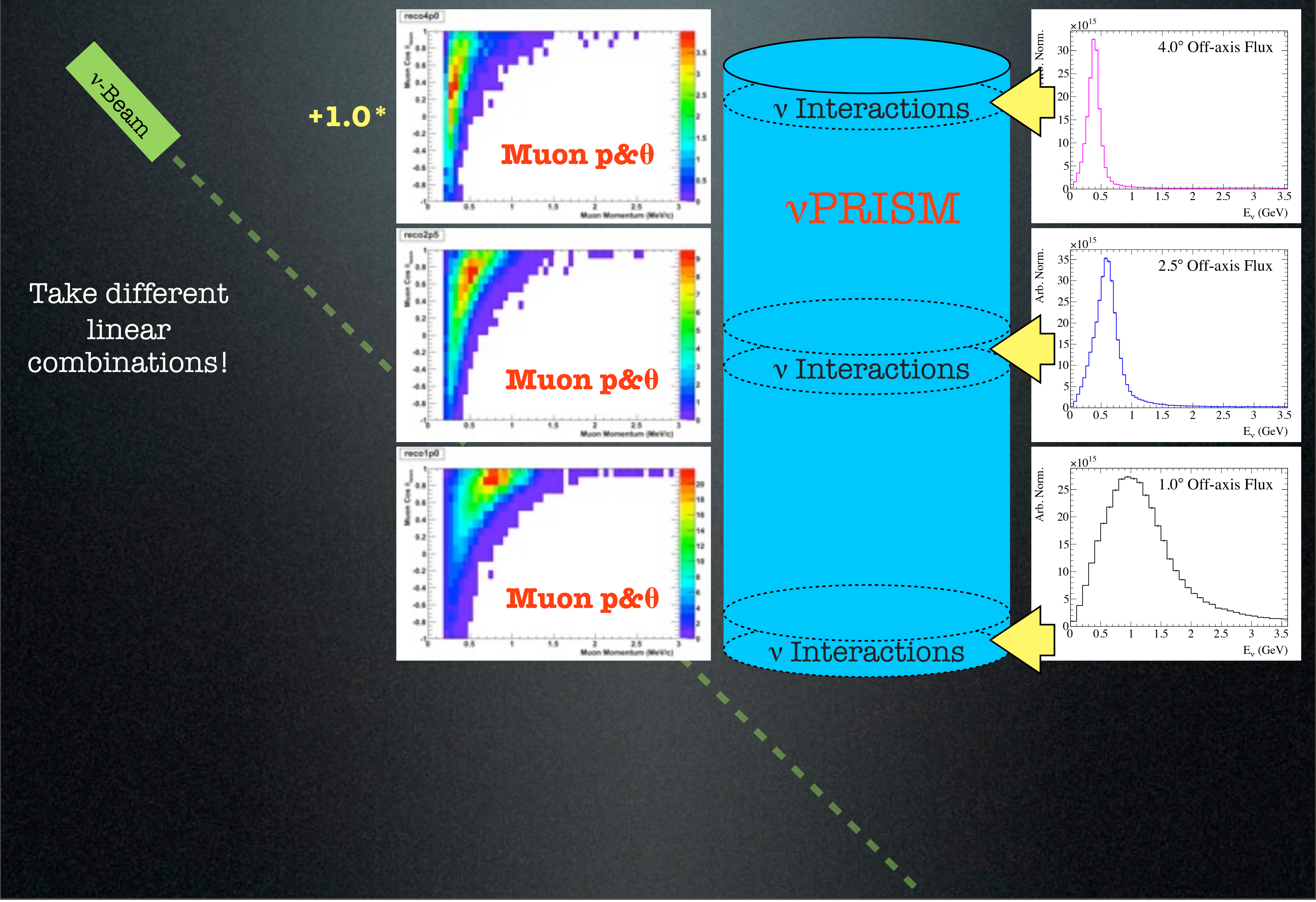

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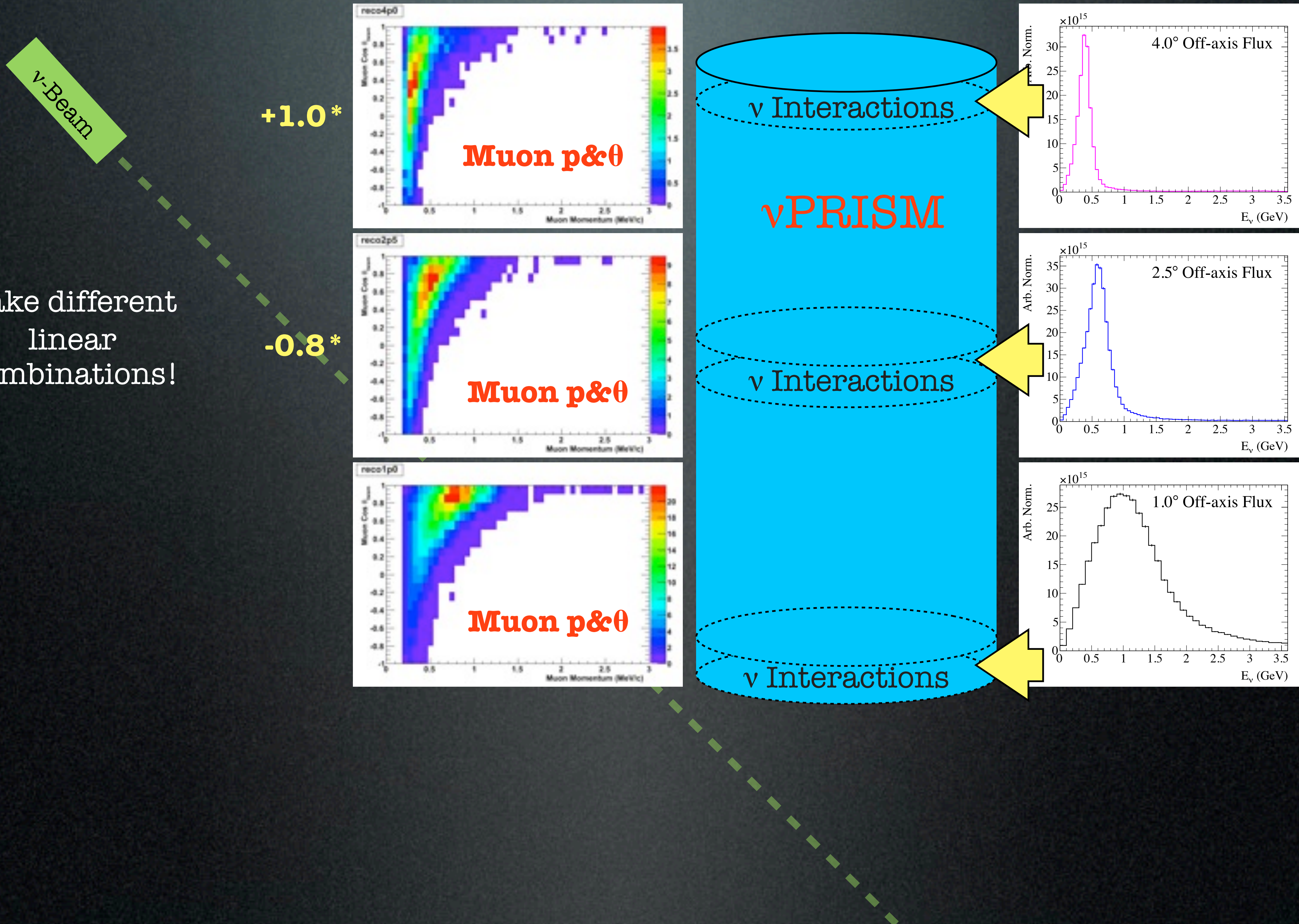
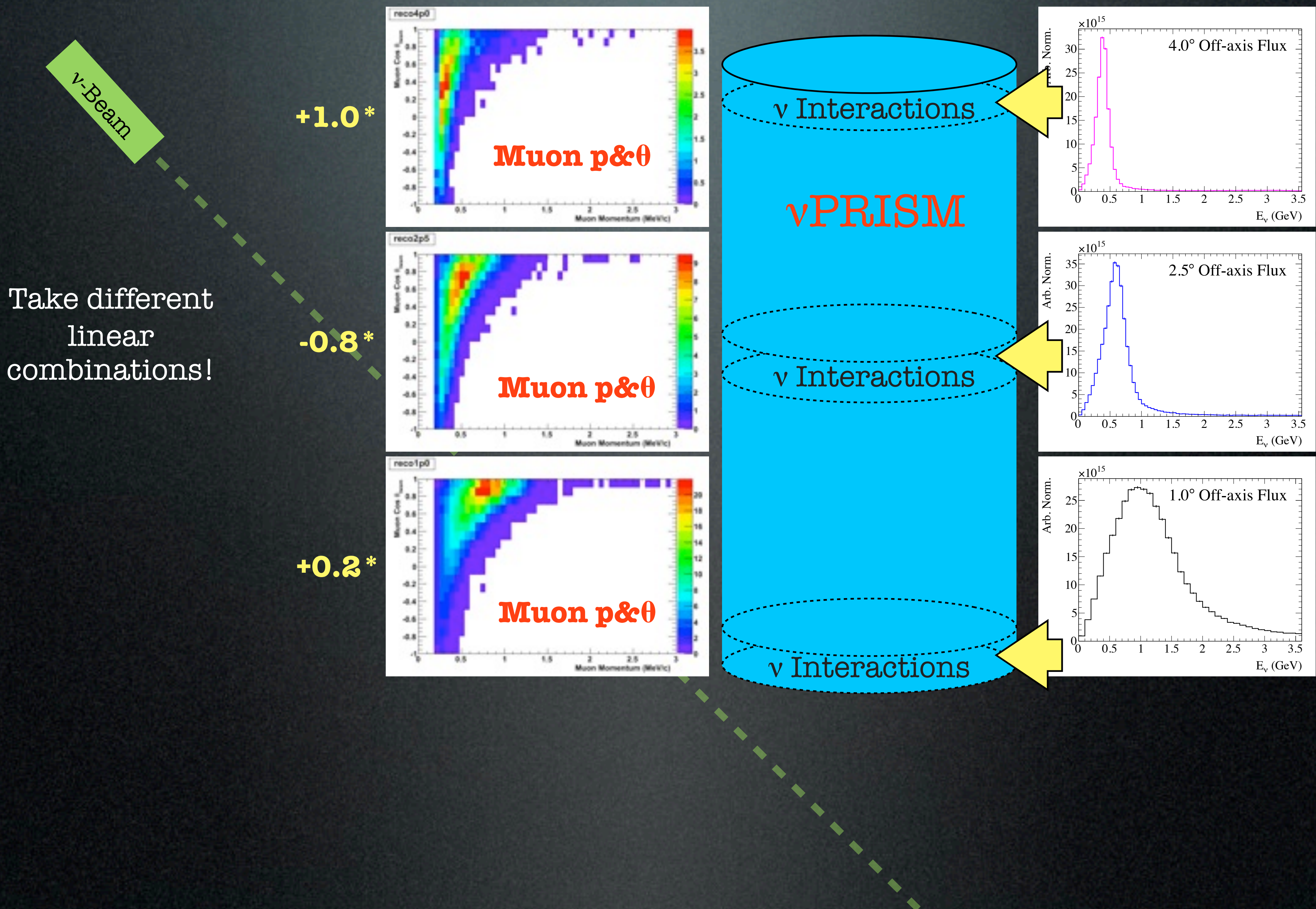


Take different linear combinations!

NuPRISM in Oscillation Experiments



NuPRISM in Oscillation Experiments

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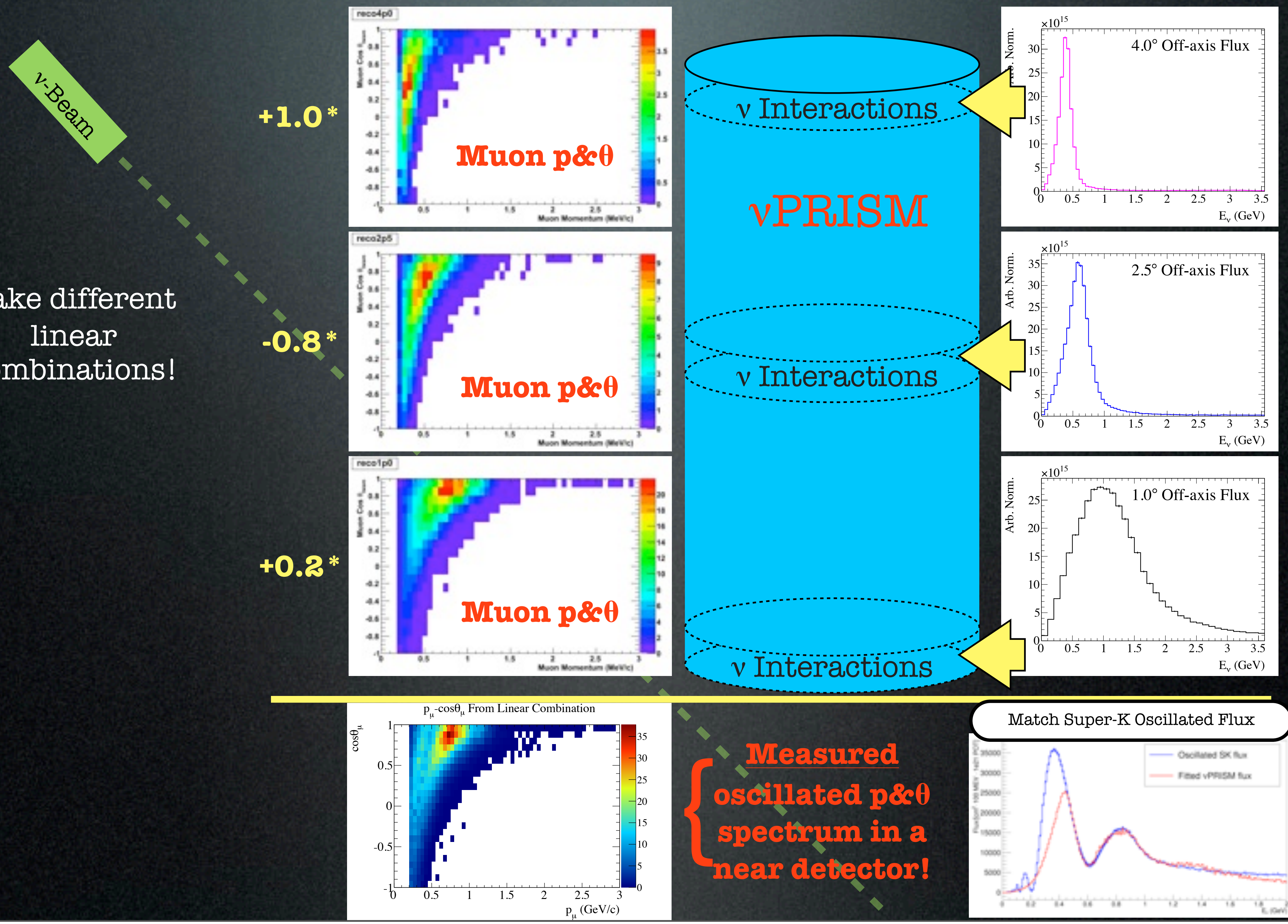

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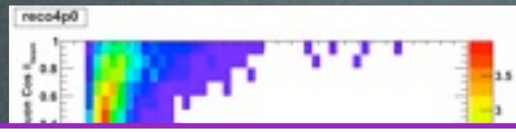
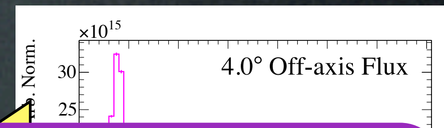
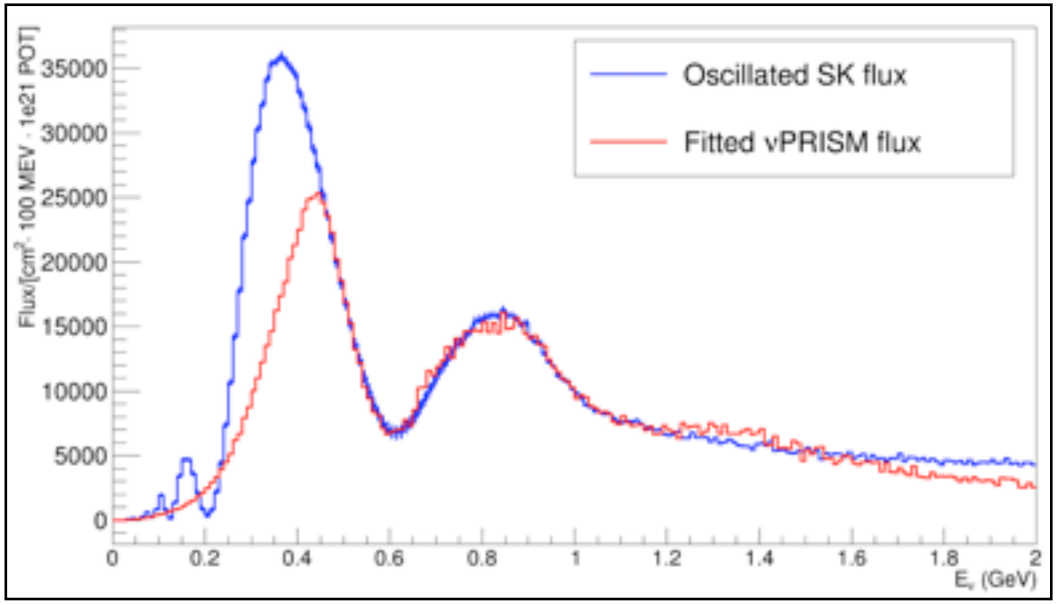
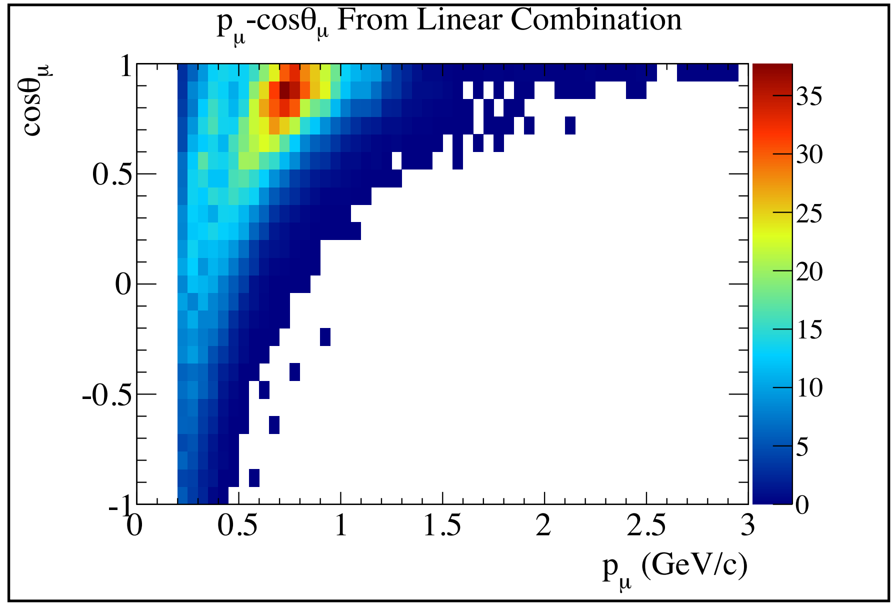


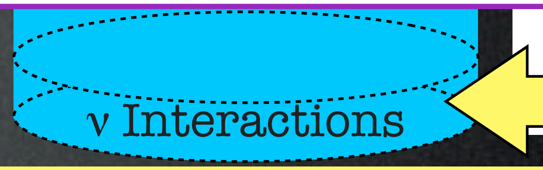


Oscillated Flux Produced at the Near Detector!



Oscillated p&θ Measured at the Near Detector!



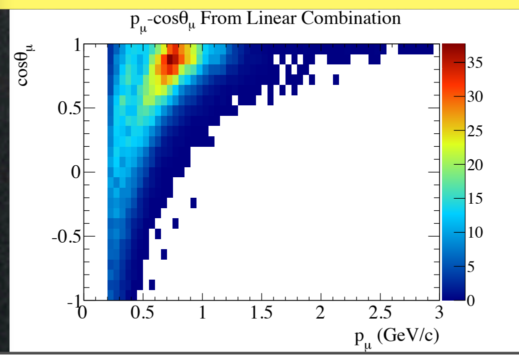


This is the procedure used for the

T2K/nuPRISM

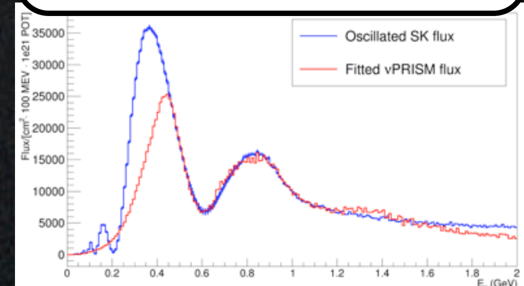
ν_μ disappearance analysis

(more later)



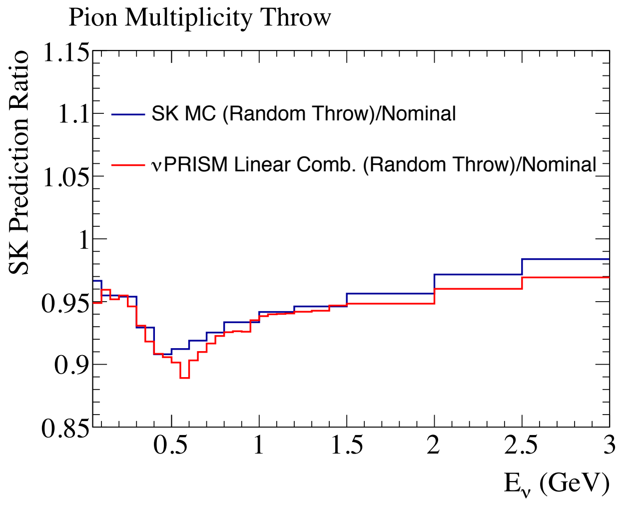
Measured oscillated p&θ spectrum in a near detector!

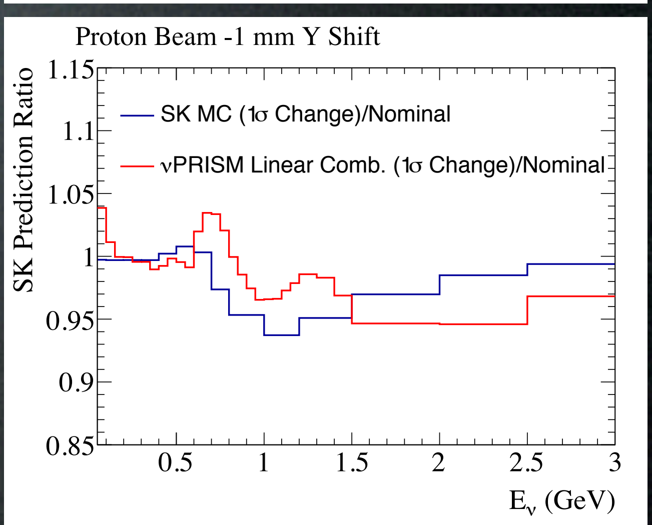
Match Super-K Oscillated Flux

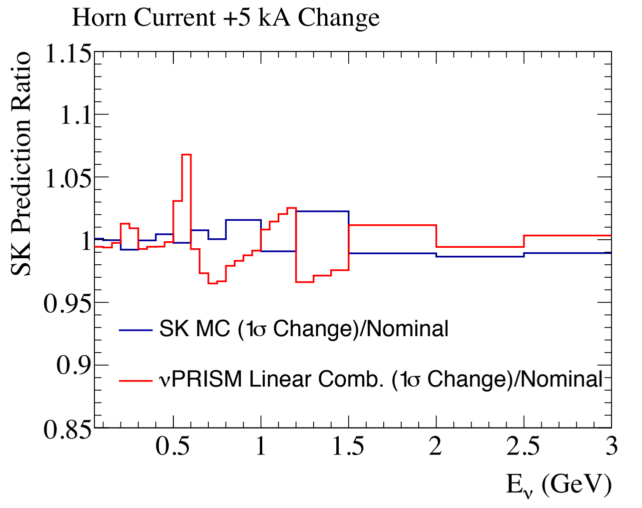


Beam Uncertainties

- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Cancelation exist between nuPRISM and far detector variations
- **Normalization uncertainties will cancel** in the NuPRISM analysis
  - Cancelations persist, even for the NuPRISM linear combination
- Variations that affect off-axis angle shape are most important
  - Horn current, beam direction, alignment, etc.
- First analyses indicate that flux variations do not significantly impact NuPRISM analyses (more later)



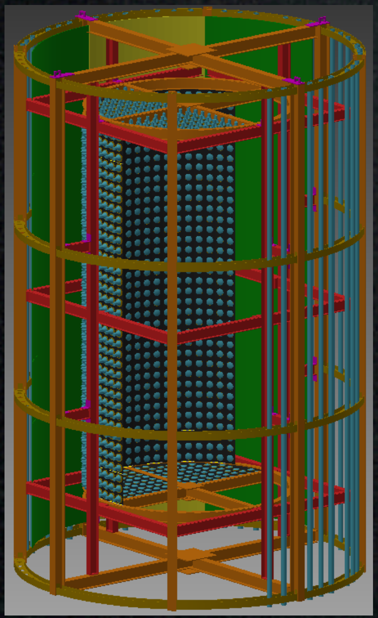


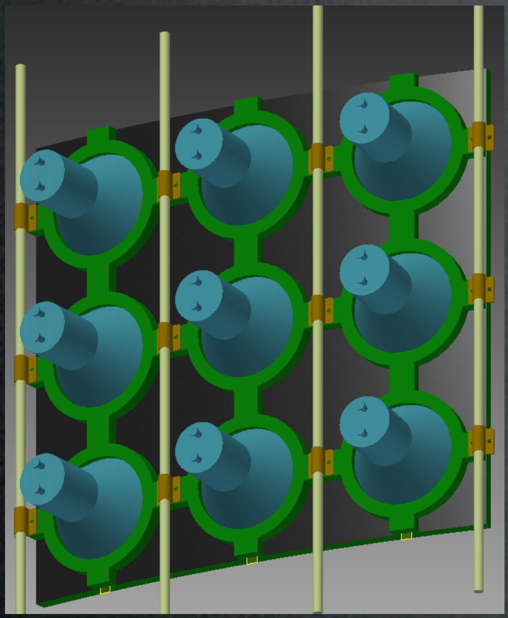


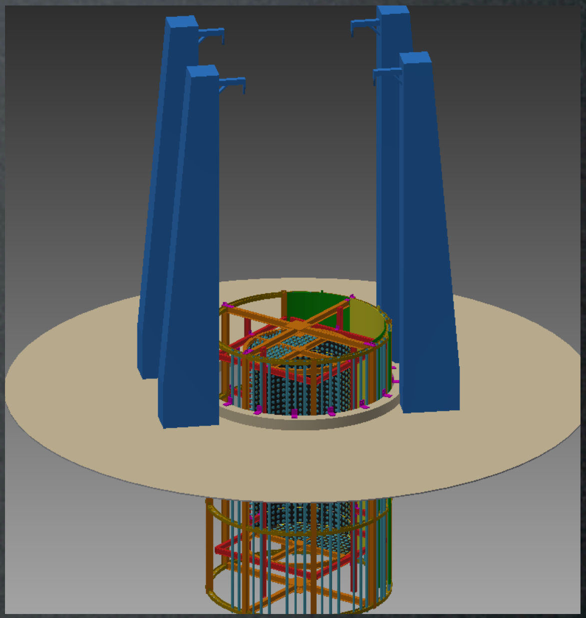
Design Considerations

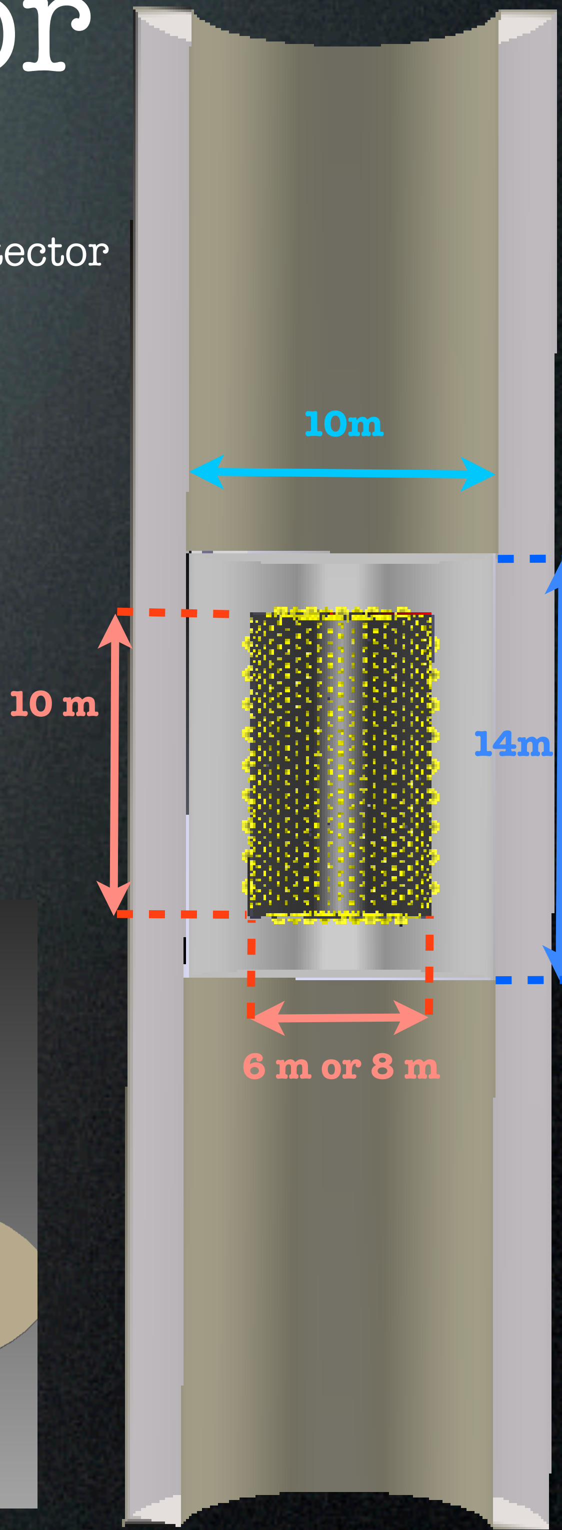
NuPRISM Detector

- At 1 km, need 50 m tall tank to span 1-4° off-axis angle
- Instrument one subsection of the tank at a time with a moveable detector
- Baseline design:
  - Inner Detector (ID): 6 m or 8 m diameter, 10 m tall
    - 8” and 5” PMTs are both under study
  - Outer Detector (OD): 10m diameter, 14m tall
    - Default plan is to use HK prototype 20” PMTs
- To improve sand muon tagging (precise entering position and time), OD is surrounded by scintillator panels

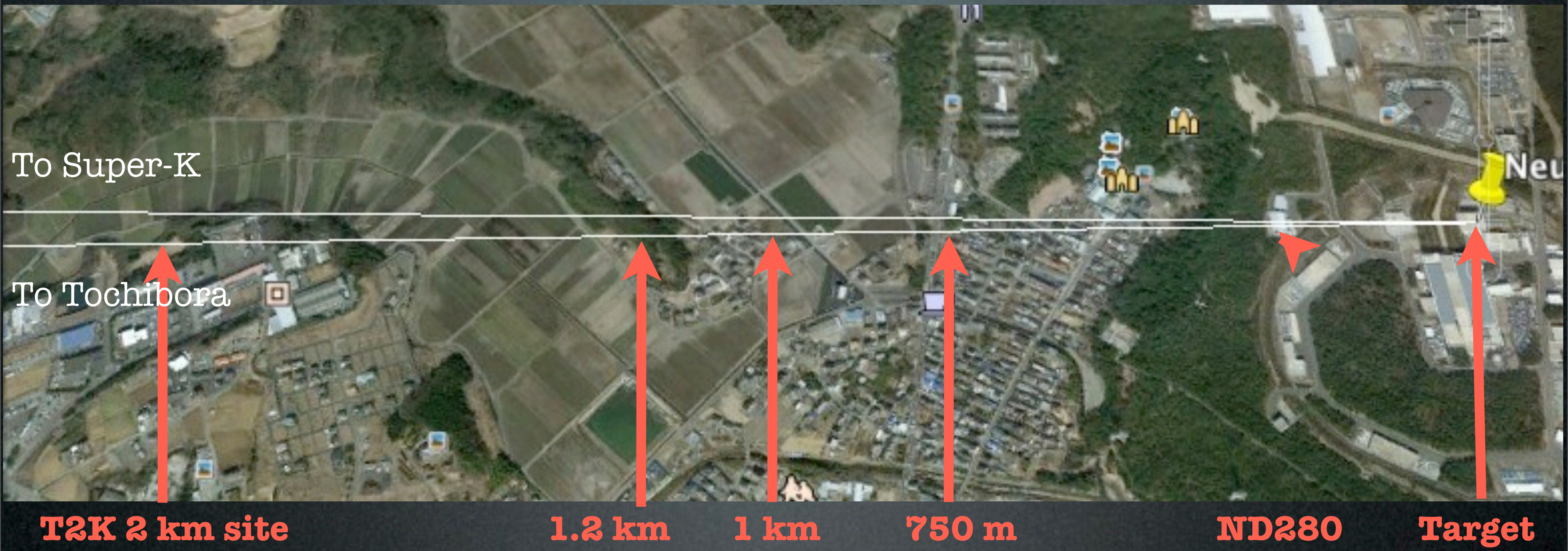








Potential Detector Locations

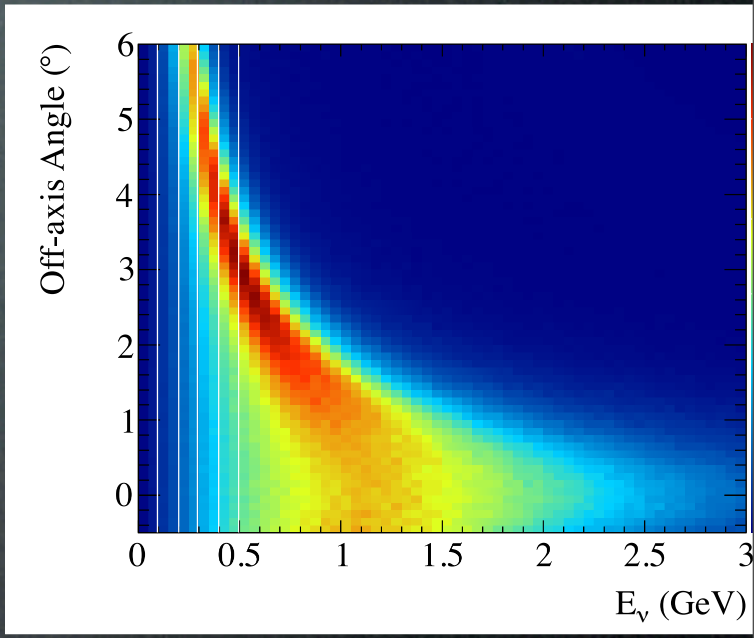


- Non-rice-field locations at 750m, 1km, and 1.2km
    - Many additional sites are available if rice fields are also considered
- Site acquisition will rely on J-PARC & KEK
    - Significant lead time is required

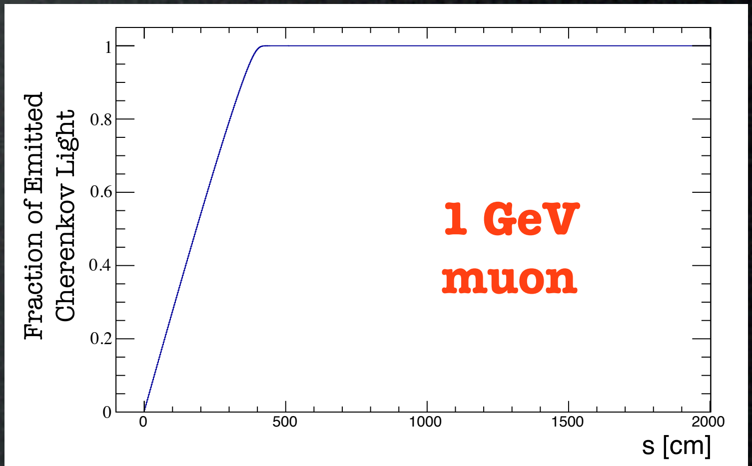
Other Design Considerations

- **Civil construction is expensive!**
  - Need to minimize excavation volume
- **Off-axis angle range (i.e. E_ν range)**
  - On-axis flux peaks at 1.2 GeV
  - 4° (6°) off-axis peaks at ~380 (~260) MeV
  - Beam points 3.63° below horizon, so get ~4° for free
- **Distance to target**
  - At 1 (1.2) km , need 54 (65) m deep pit to span 1°-4°
  - Event pileup must be manageable
- **Tank diameter**
  - Determines maximum muon contained
    - 4 m (+ FV cut) for 1 GeV/c muon
  - PID degrades near the wall
    - Important for selecting e-like events
  - Larger = more stats, but also more pileup
  - Larger = more PMTs = more expensive
  - How much outer detector is necessary?

Off-axis Fluxes



Muon Range



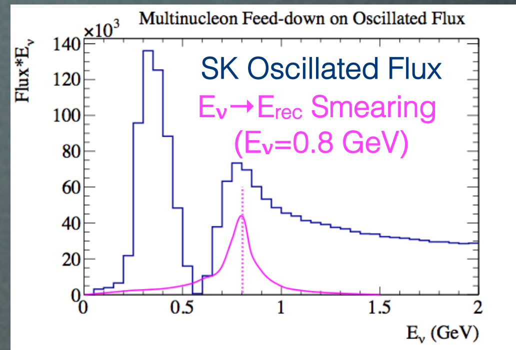
The nuPRISM ν_μ Disappearance Analysis

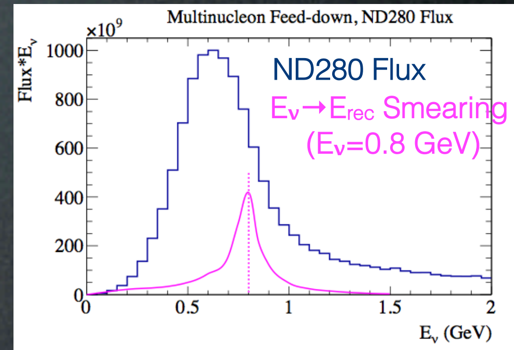
Most straightforward to perform, and directly impacts sensitivity to CP violation

Reminder: Standard Oscillation Experiment Technique

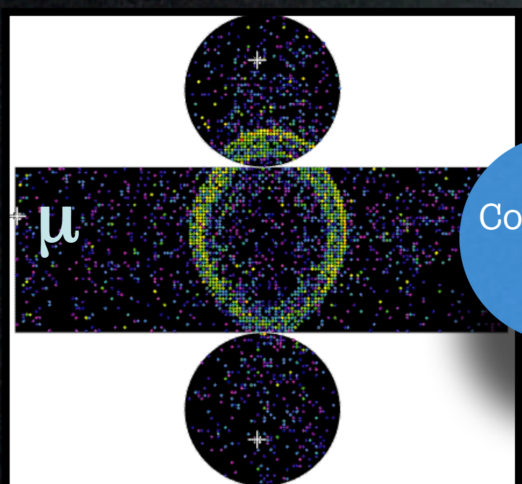
Different near and far detector fluxes do not allow for a precise feed-down constraint at the near detector

Must resort to constraining parameters in models known to be incorrect





Observed far detector signal:
1-ring muon events



Composed Of:

Nuclear model

CCQE: $\mu^- + p$ (p unobserved)

CCπ^+: $\mu^- + N + \pi^+$ (p, π^+ unobserved)

CCDIS: $\mu^- + X$ (X unobserved)

NCπ^+: $\pi^+ + n$ (π^+ misidentified, n unobserved)

...

Predicted by poorly understood models

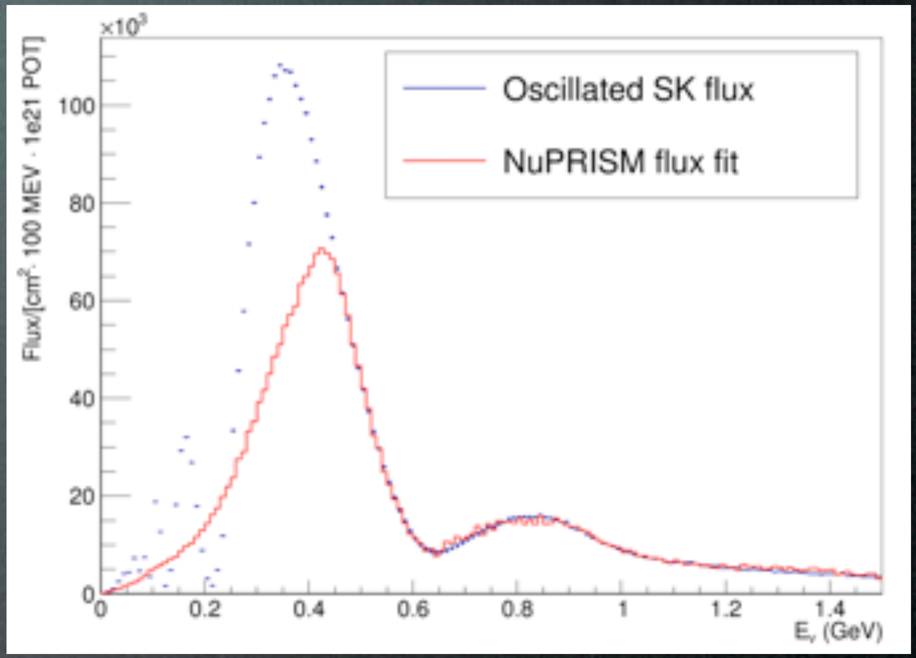
Parameter	E_ν Range	Nominal	Error	Class
M_A^{QE}	all	1.21 GeV/c^2	0.45	shape
M_A^{RES}	all	1.41 GeV/c^2	0.11	shape
p_F ^{12}C	all	217 MeV/c	30	shape
E_B ^{12}C	all	25 MeV	9	shape
SF ^{12}C	all	0 (off)	1 (on)	shape
CC Other shape ND280	all	0.0	0.40	shape
Pion-less Δ Decay	all	0.0	0.2	shape
CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11	norm
CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30	norm
CCQE E3	$E_\nu > 3.5$	1.0	0.30	norm
CC1π E1	$0 < E_\nu < 2.5$	1.15	0.43	norm
CC1π E2	$E_\nu > 2.5$	1.0	0.40	norm
CC Coh	all	1.0	1.0	norm
NC1π^0	all	0.96	0.43	norm
NC 1$\pi^\pm$	all	1.0	0.3	norm
NC Coh	all	1.0	0.3	norm
NC other	all	1.0	0.30	norm
ν_μ/ν_e	all	1.0	0.03	norm
$\nu/\bar{\nu}$	all	1.0	0.40	norm

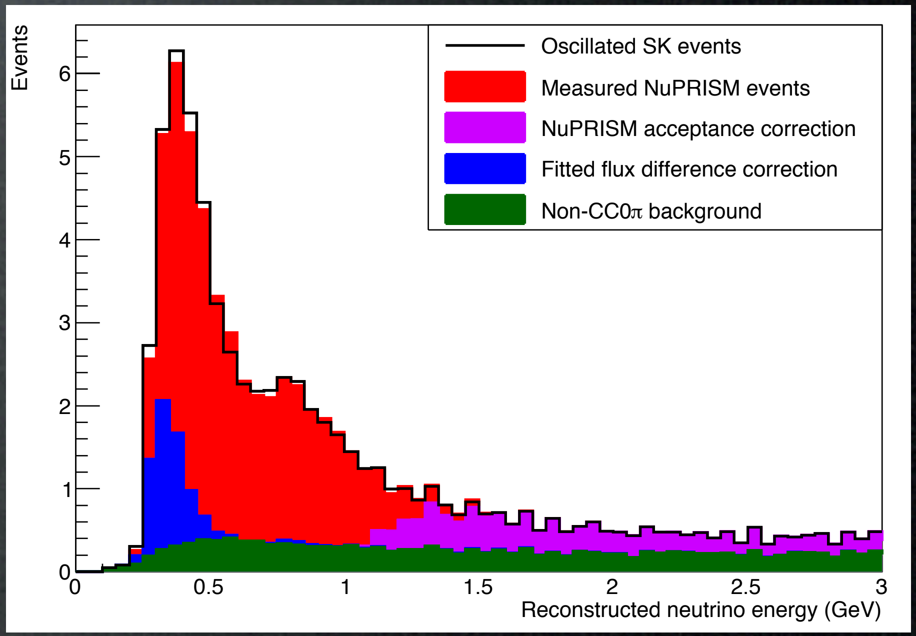
Simultaneously constrain flux and cross section parameters with a near detector

Often with a different nuclear target and phase space

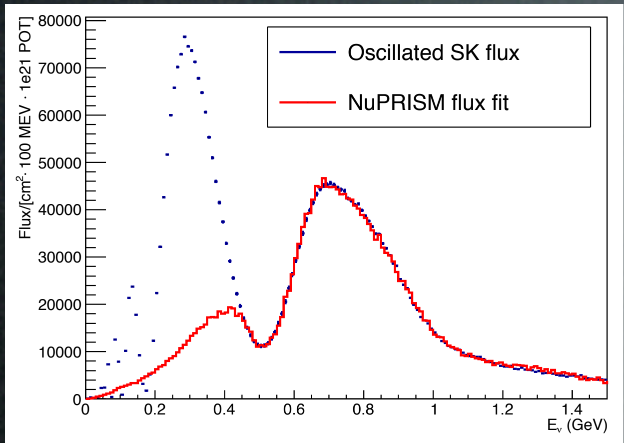
NuPRISM Technique

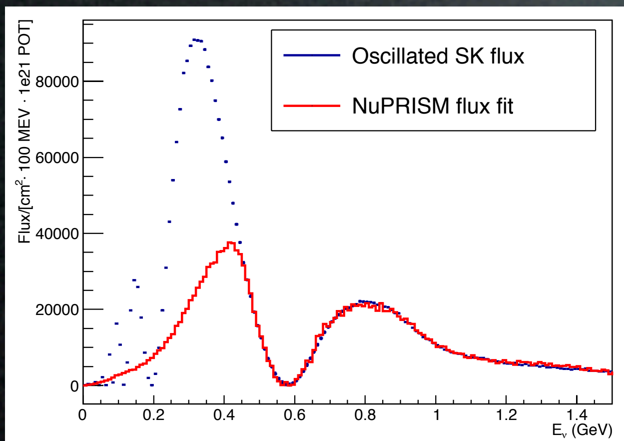
- Flux is now the same at the near and far detector
  - **Can just measure observed muon p vs θ for any oscillated flux**
- Same signal selection as used at Super-K
  - Single, muon-like ring
- **Signal events** are defined as **all true single-ring, muon-like events**
  - A muon above Cherenkov threshold
  - All other particles below Cherenkov threshold
  - Signal includes CCQE, multi-nucleon, $CC\pi^+$, etc.
- **No need to make individual measurements of each process and extrapolate to oscillated E_ν spectrum**
  - Some corrections are needed for different detector acceptance, flux fit differences, and remaining backgrounds

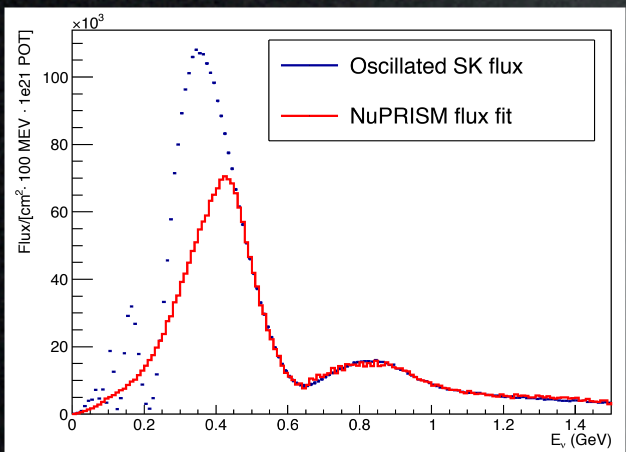




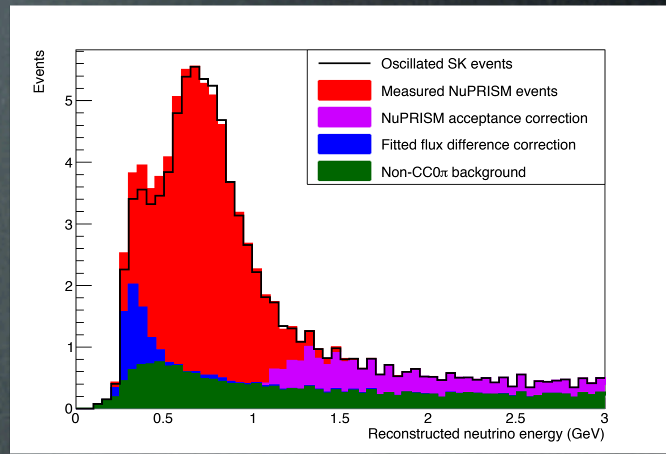
“Oscillations” in a Near Detector

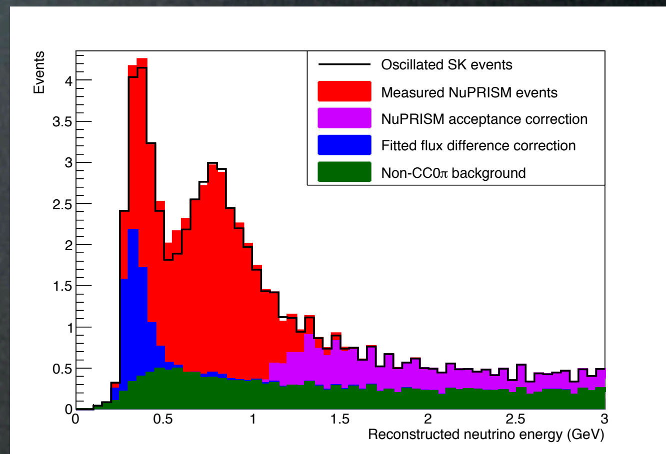


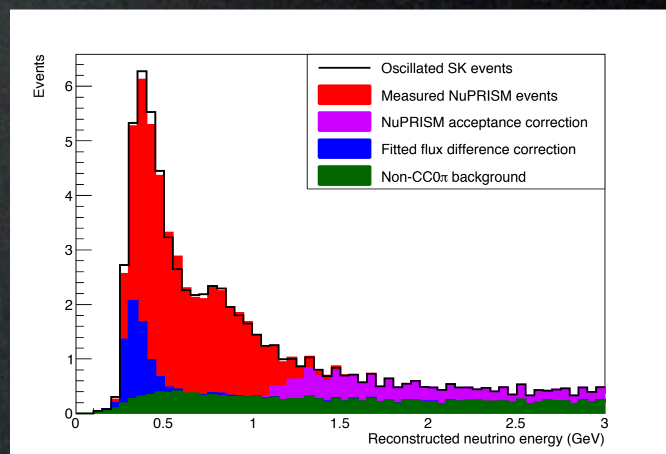




- Red region is directly measured by NuPRISM
- Blue region is flux difference correction
- Green is SK non-CC0π background
  - Partially cancels with already-subtracted NuPRISM CC0π background
- Magenta is acceptance correction
  - (geometric muon acceptance)
- SK prediction is largely from directly measured component

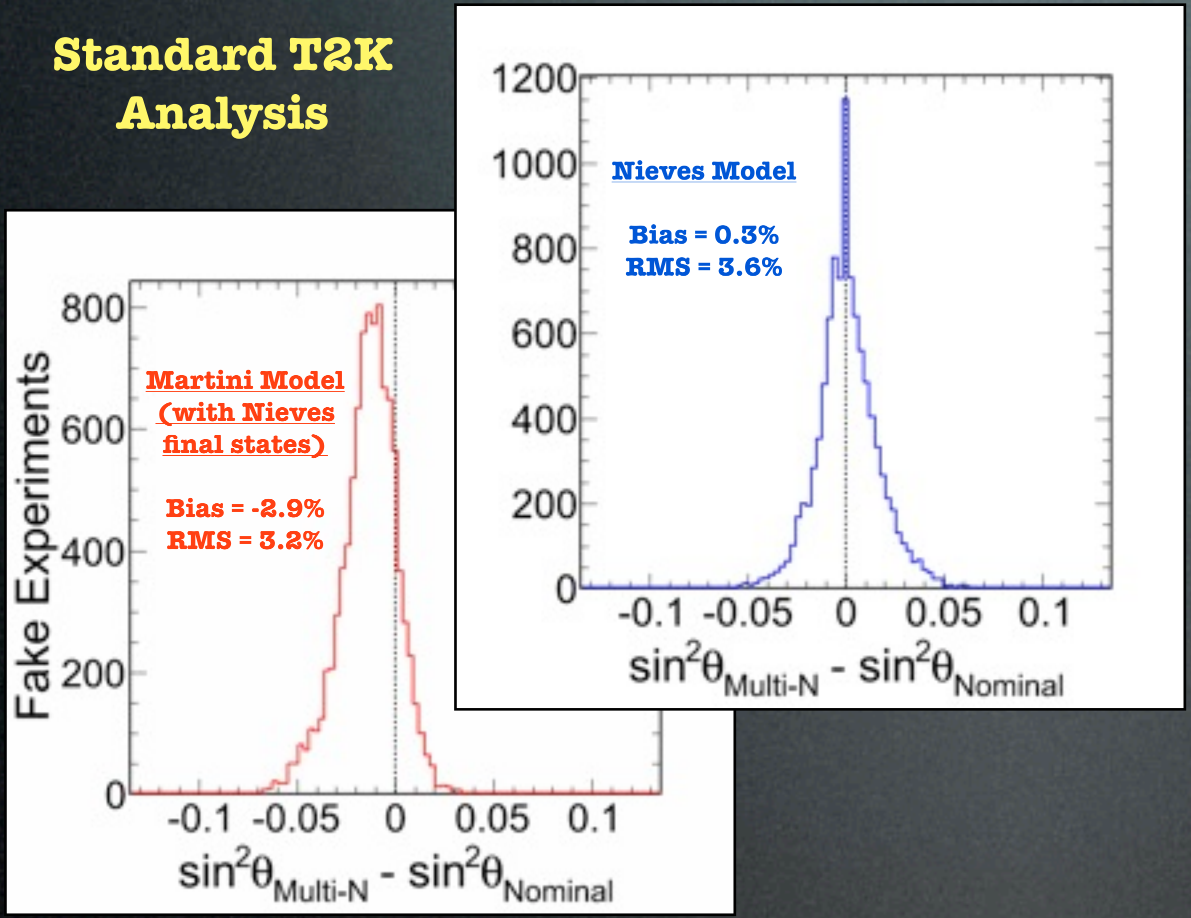






NuPRISM ν_μ Disappearance Constraint

Standard T2K Analysis



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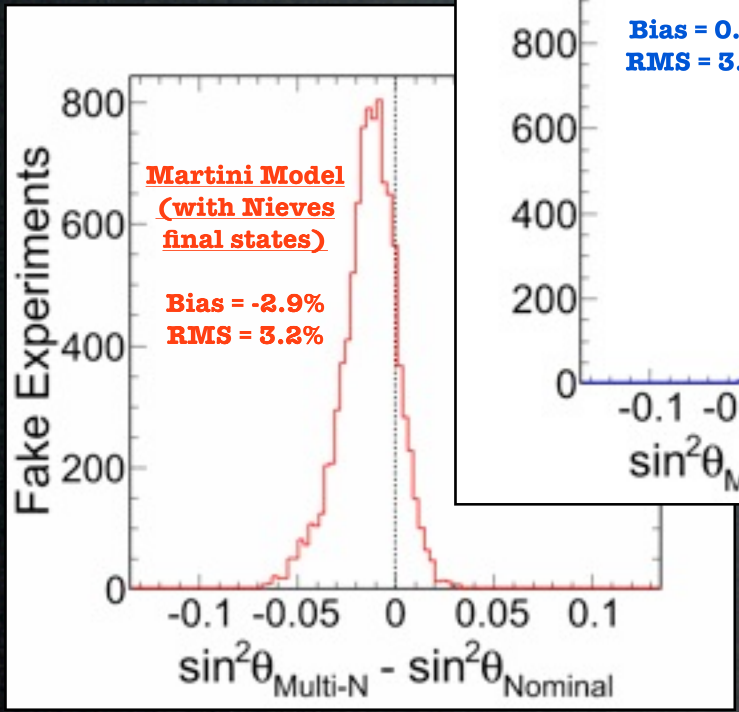

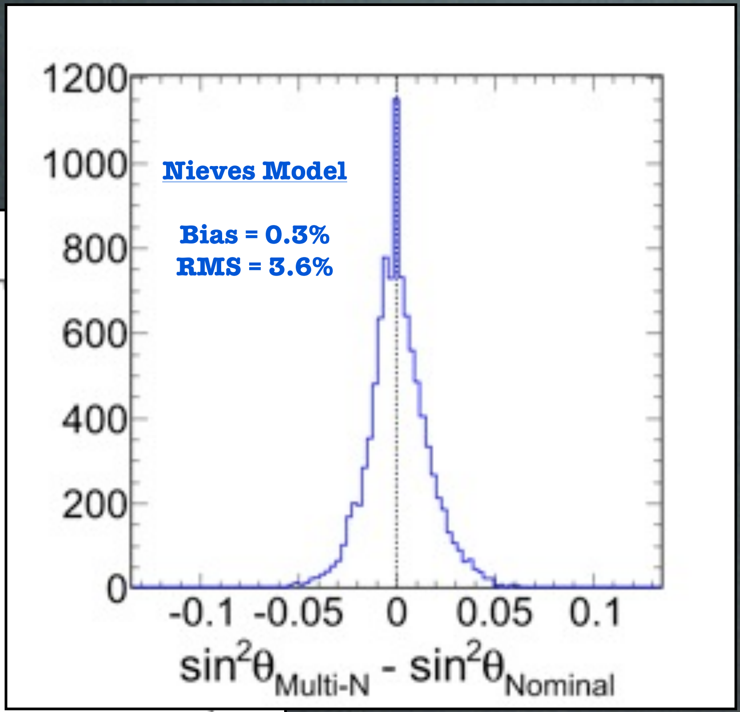

νPRISM Analysis

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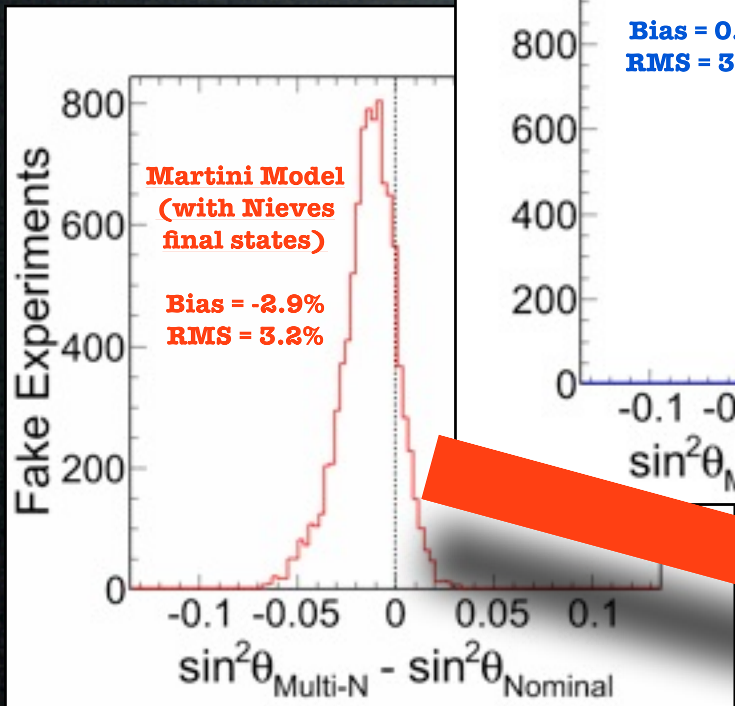

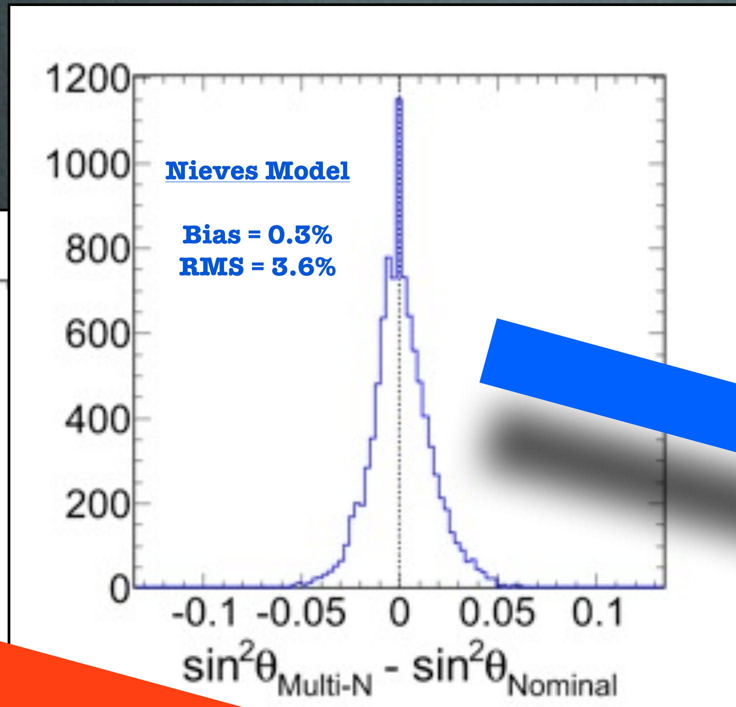

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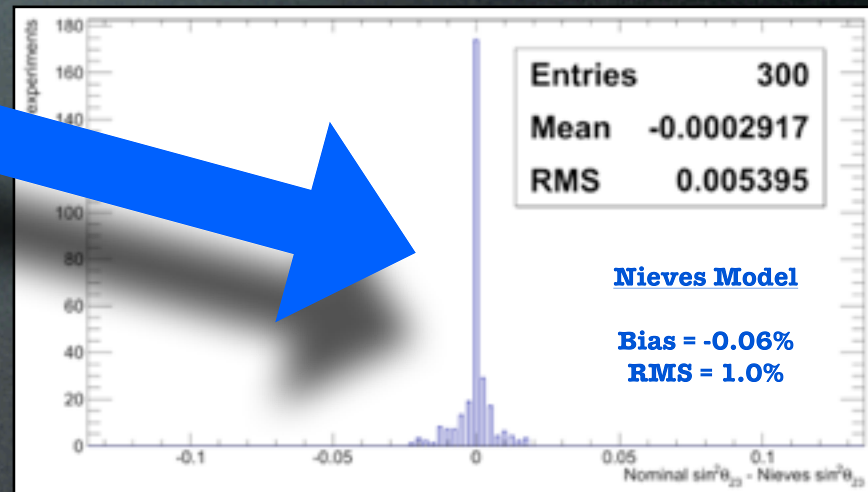

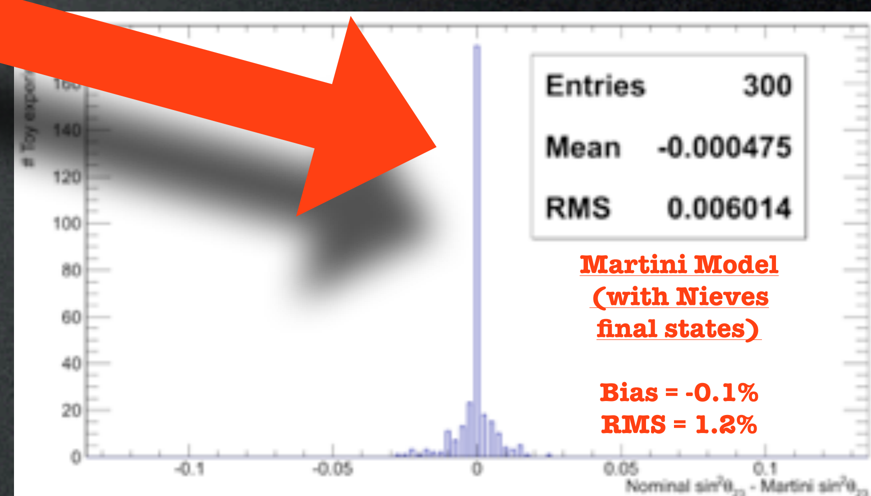

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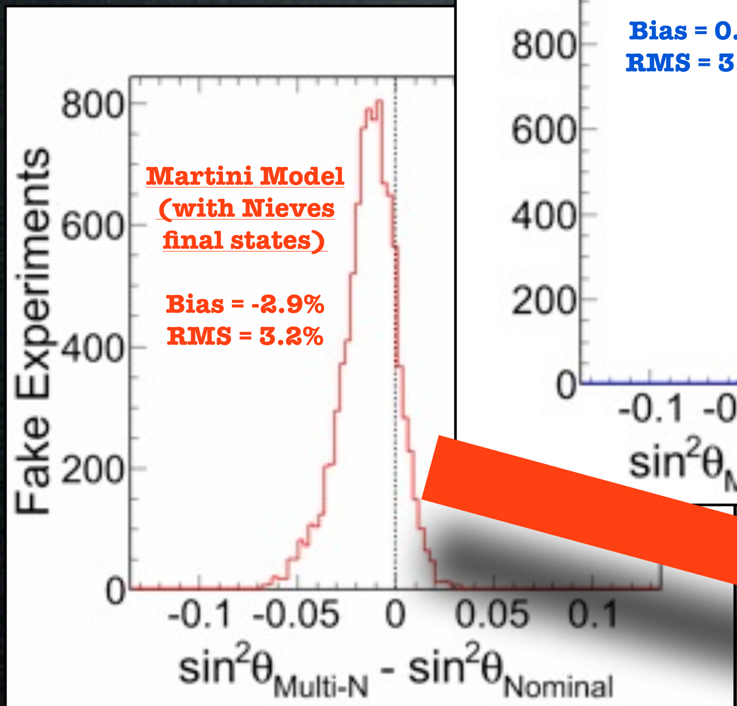

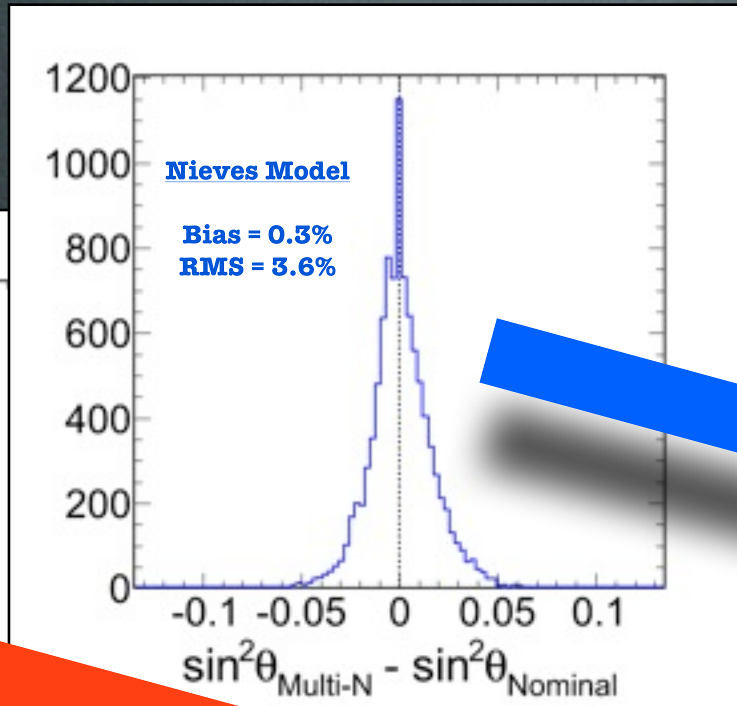

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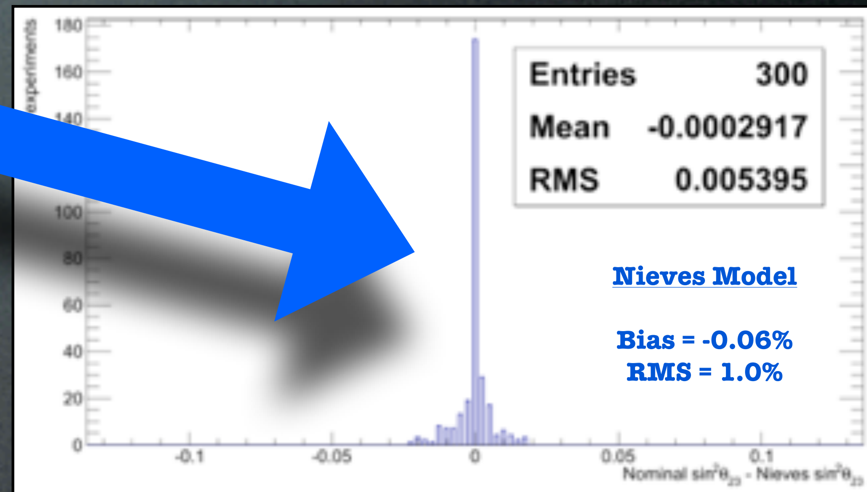

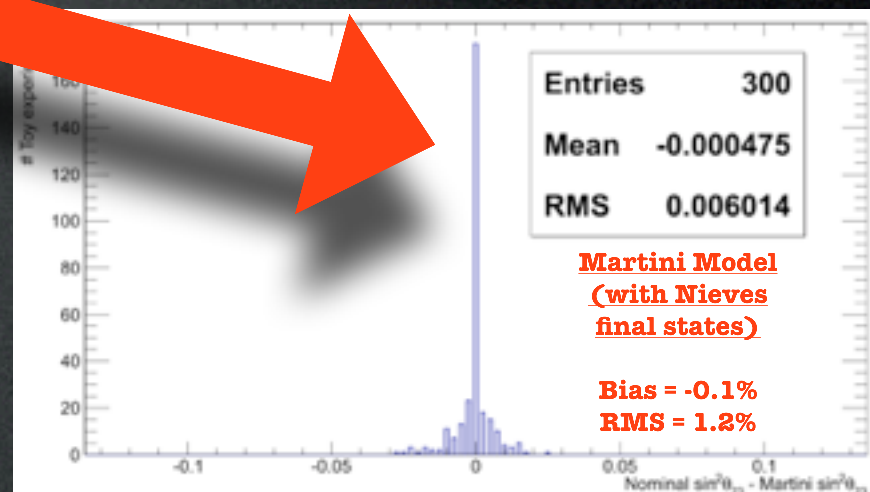

- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**

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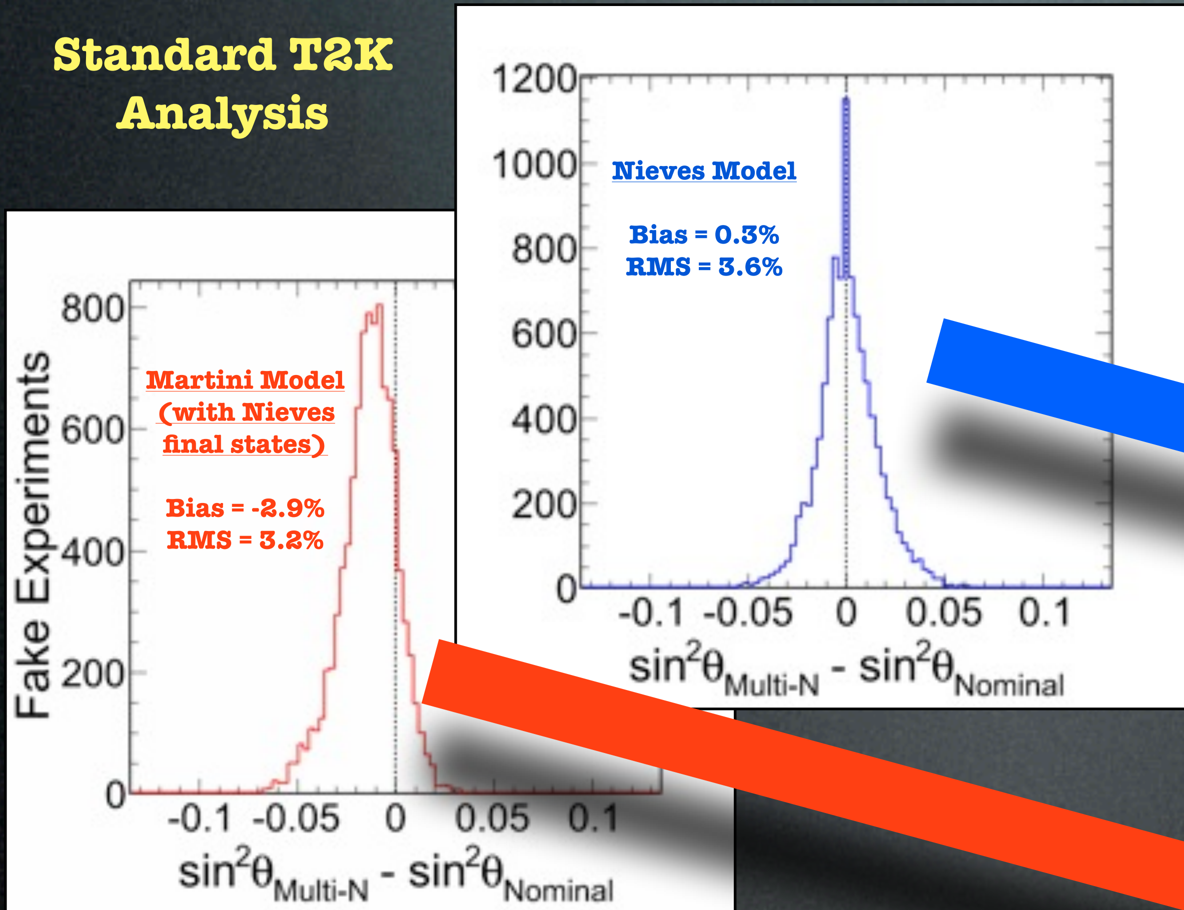

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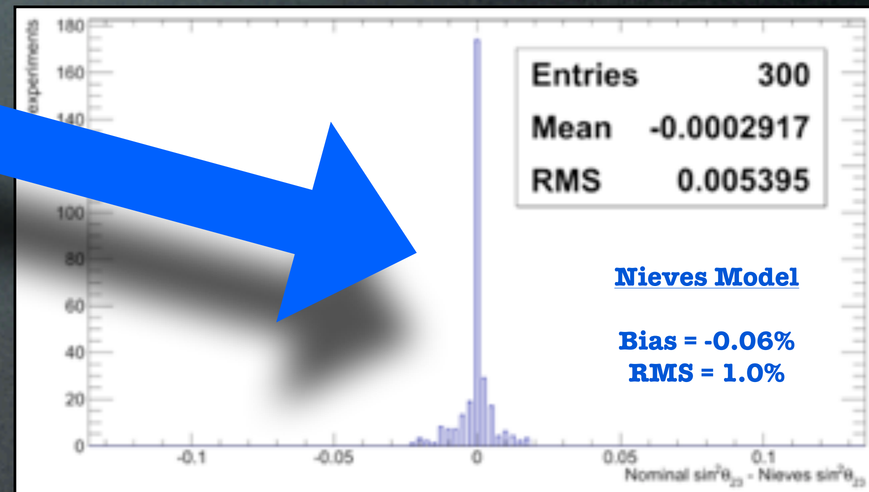

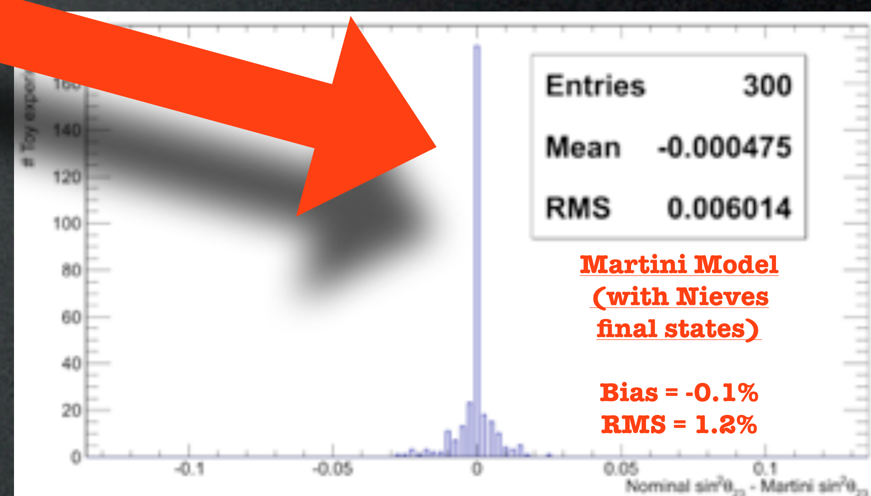

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- More importantly, this is now based on a **data constraint**, rather than a model-based guess

NuPRISM ν_μ Disappearance Constraint

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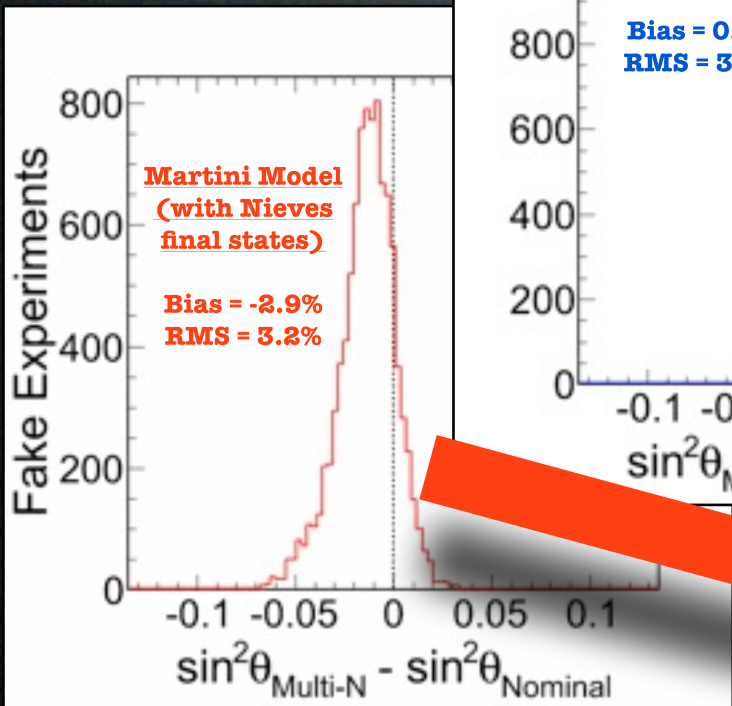

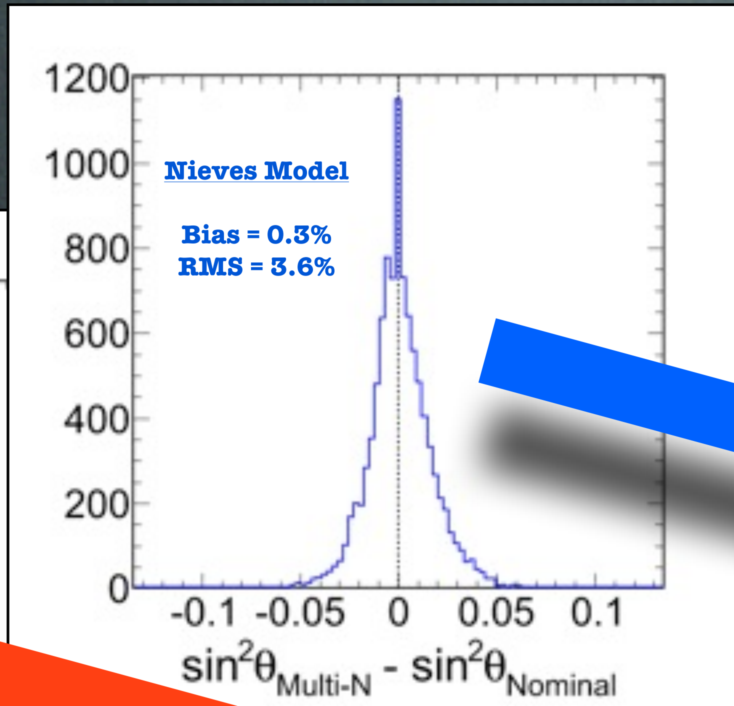

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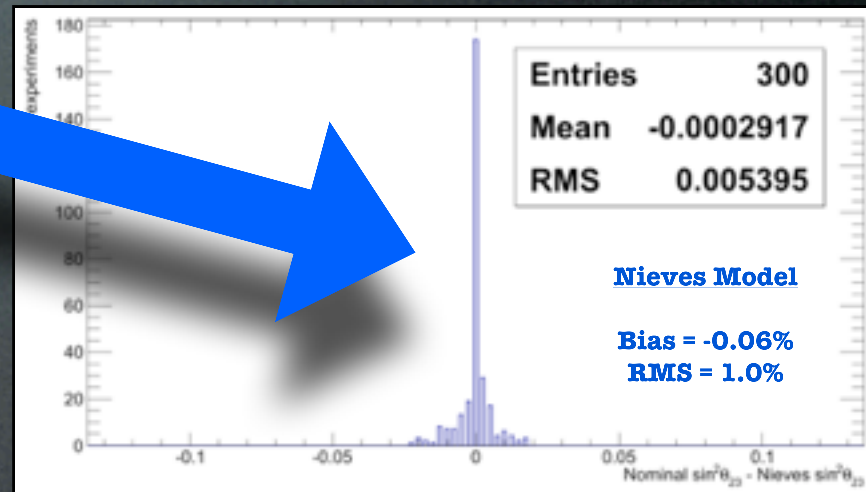
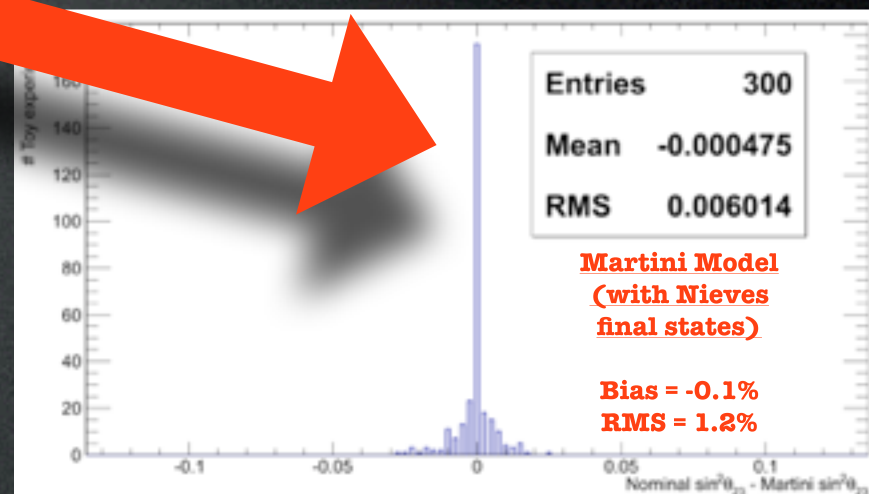




- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the NuPRISM constraints to get significantly better as additional constraints are implemented (very conservative errors)

NuPRISM CP Violation Measurement

T2K and T2K-II Systematics

Fractional error on number-of-event prediction

2014 → 2015 → 2016(work-in-progress)

		ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ν flux		16%	11%	7.1%	8.0%				
ν flux and cross section	w/o ND meas.	21.8%	26.0%	9.2%	9.4%				
	w/ ND meas.	2.7%	3.1%	3.4%	3.0%	2.6%	3.0%	3.0%	3.5%
ν cross section due to difference btw. near and far detector		5.0%	4.7%	10%	9.8%	0.7%	3.0%	0.7%	3.3%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%	1.8%	2.6%	2.4%	2.7%
Super-K detector		4.0%	2.7%	3.8%	3.0%	4.6%	2.8%	3.9%	4.0%
total	w/o ND meas.	23.5%	26.8%	14.4%	13.5%				
	w/ ND meas.	**7.7%**	**6.8%**	**11.6%**	**11.0%**	**5.6%**	**5.7%**	**5.5%**	**6.8%**

* 2014 error does not include the effect of multinucleon at the neutrino-nucleus interaction (those are separately treated), but now it is included.

* improved modeling of multinulceon interaction and analysis of FGD2(w/ water) data

- Adding multi-nucleon events in 2015 significantly increase the systematic error
- In 2016, errors were reduced by measuring ND280 water interactions
  - However, work is still underway to add multi-nucleon shape errors

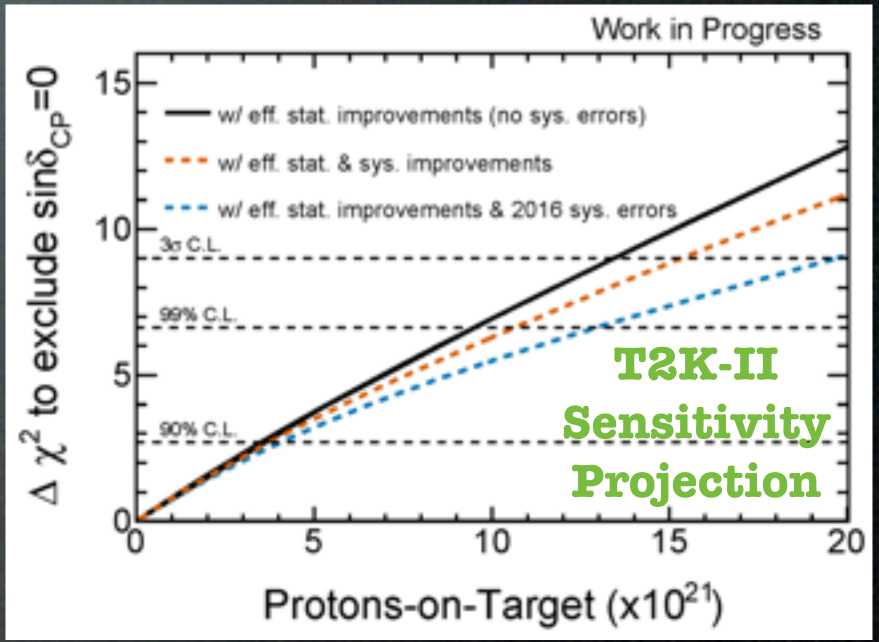
2016 T2K Uncertainties

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	4.6	3.9	2.8	4.0	1.9
SK Final State & Secondary Interactions	1.8	2.4	2.6	2.7	3.7
ND280 Constrained Flux & Cross-section	2.6	3.0	3.0	3.5	2.4
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.4	2.7	1.5
NC Other Cross-section	0.7	0.7	0.2	0.3	0.2
Total Systematic Error	5.6	5.5	5.7	6.8	5.6
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.2	4.0	0.1

- CPV sensitivity depends on the uncertainty in the ν_e/anti-ν_e ratio (5.6%)
- Dominant uncertainties come from theoretical estimates
  - SK Final State Interactions (model extrapolation of $\pi^{\pm}$-N scattering data to nuclear environment)
  - $\sigma_{\nu e}/\sigma_{\nu\mu}$ (ND280 cannot constrain ν_e interactions to this level)
- Current uncertainty in Multi-nucleon events contains no shape uncertainty
  - Adding shape uncertainty is likely to increase this error

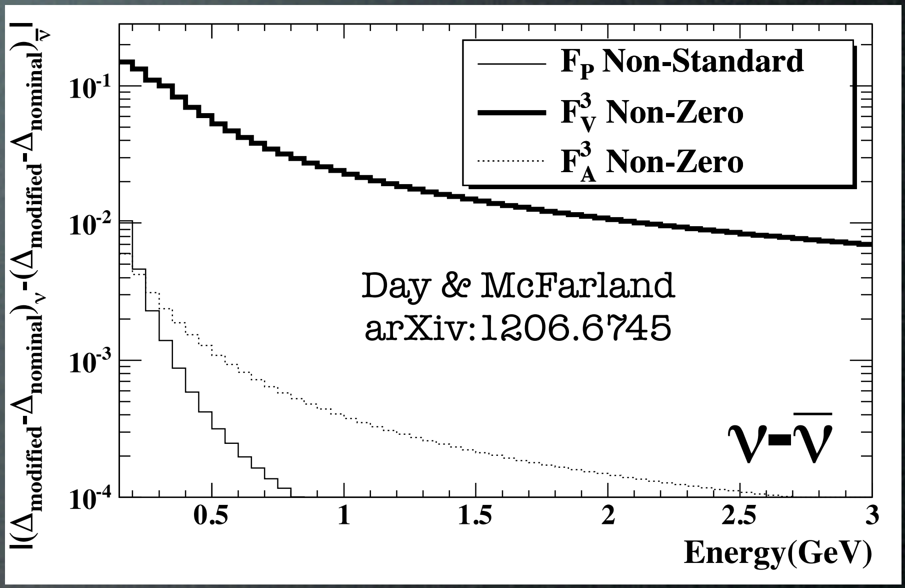
T2K CPV Physics Reach

- With 20 x 10^{21} POT, T2K-II can achieve 3σ CPV sensitivity if:
  - 50% increase in ν_e efficiency
  - ν_e/anti-ν_e error remains at 5.6%
  - $\delta_{CP} = -\pi/2$
- At full POT, systematic errors have a large impact on the sensitivity
- Additional improvement is systematic errors would allow T2K-II to:
  - Reach 3σ sensitivity earlier
  - Reach 3σ sensitivity for a wider range of δ_{CP}
  - Achieve a more robust 3σ discovery
- We have an opportunity to achieve 3σ evidence for CPV, so every improvement in statistical and systematic uncertainty is critical
  - A statistics limited measurement is strongly preferred



Constraining δ_{CP} with NuPRISM

- The **strong constraints on ν_μ** interactions provided by NuPRISM will provide a lot of information about nuclear effects in ν_e interactions
- However, there may still be some differences between ν_e and ν_μ cross sections (e.g. 2nd class currents?)
- How do we constrain ν_e events?
    - Intrinsic ν_e in beam
        - Requires a large detector with the same nucleus and acceptance as the far detector
        - **NuPRISM**!
- NuPRISM can also largely remove the flux differences between ν_μ and ν_e (next slide)



Need to measure:

$\sigma(\nu_\mu)/\sigma(\bar{\nu}_\mu)$

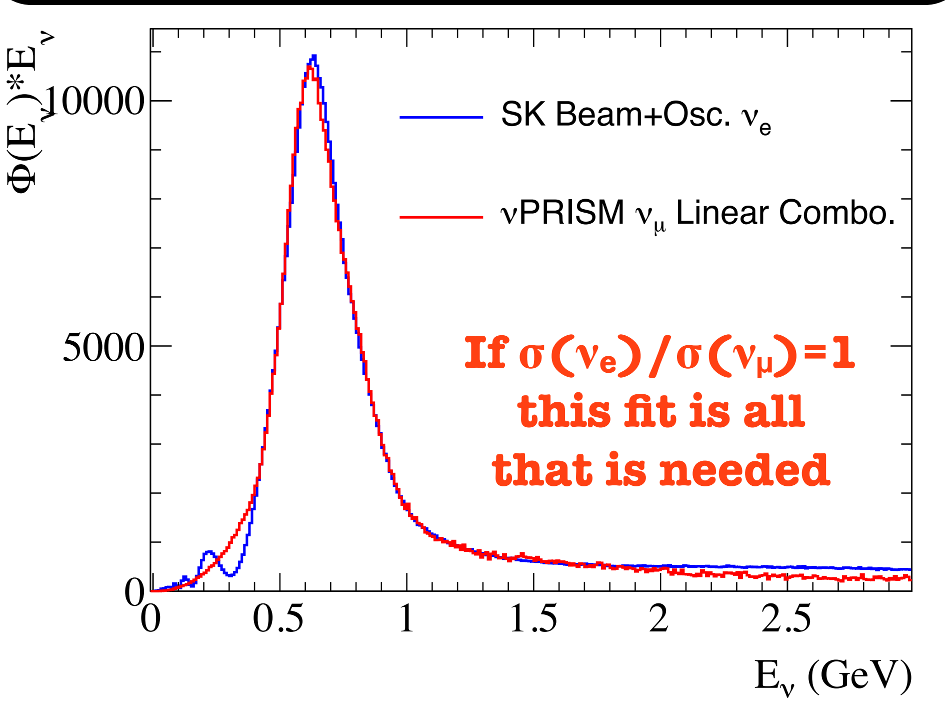
$\sigma(\nu_e)/\sigma(\nu_\mu)$

$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$

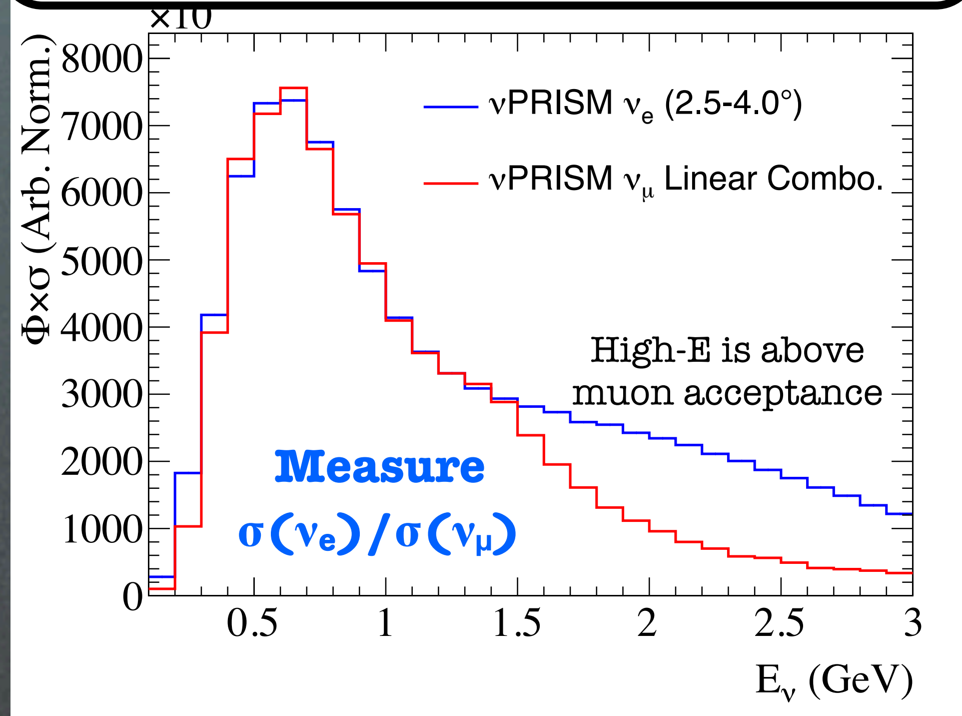
NuPRISM ν_e Appearance (CPV)

3 step approach:

Step 1: Measure **Super-K** ν_e response with NuPRISM ν_μ



Step 2: Measure **NuPRISM** ν_e response with NuPRISM ν_μ



- Step 1 is the ν_e version of the ν_μ disappearance analysis
  - Reduces FSI/SI and SK detector uncertainties, and improves ND280 flux+xsec constraint
- Step 2 uses only NuPRISM to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - Constrains the $\sigma(\nu_e)/\sigma(\nu_\mu)$ uncertainty
- Step 3 uses the 2.5° slice of NuPRISM to measure NC backgrounds with the same energy spectrum as the far detector (reduces background systematics)

Constraining the ν_e Cross Section

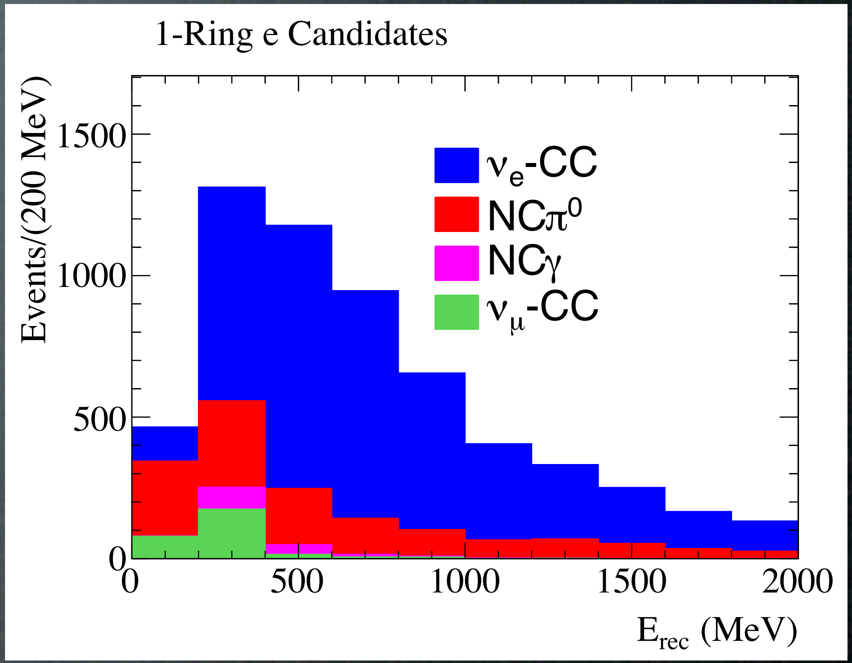
- Water Cherenkov detectors can achieve high ν_e purities
    - In T2K, we can achieve a **77% ν_e purity** at Super-K
- Studies to optimize PMT size/granularity to maximize ν_e purity in NuPRISM are ongoing
- NuPRISM ν_e analysis uses 2.5°-4.0° in off-axis angle range

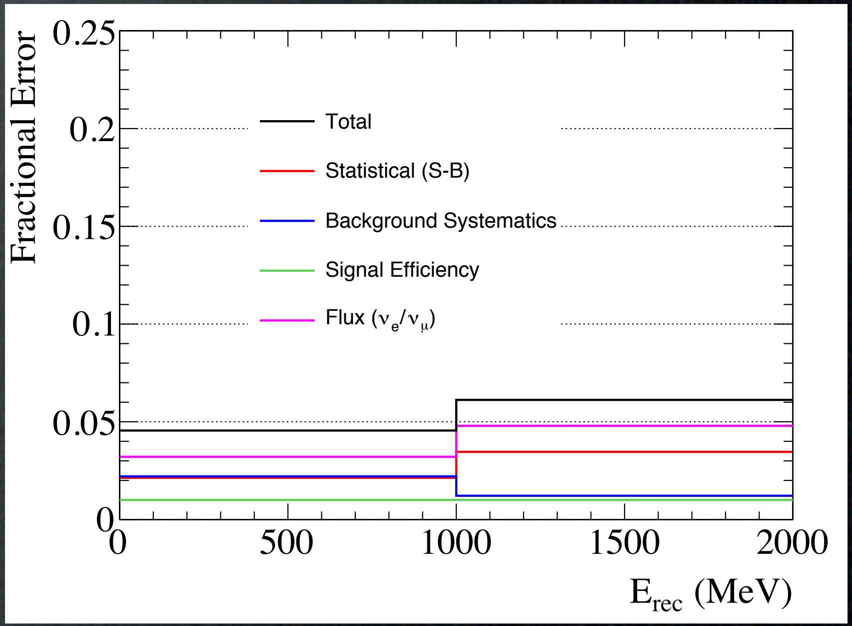
50% increase in ν_e fraction from 2.5° to 4.0° off-axis

Off-axis angle (º)	ve Flux 0.3-0.9 GeV	vμ Flux 0.3-5.0 GeV	Ratio ve/vμ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

First NuPRISM ν_e Selection

- 6 m inner detector diameter (**plan to increase to 8 m**)
  - π^0 rejection does not yet include outer detector cut
- "Out-of-the-box" reconstruction is already working well!
  - 3500 events with 71% purity
  - **Further reconstruction improvements coming soon**
- Can already achieve <5% total error with:
  - 50% uncertainty on NC1γ
  - 5% uncertainty on other backgrounds from in-situ measurements
    - **These may be improved with exclusive analyses**
  - 1% uncertainty on signal efficiency
- Flux uncertainties are the largest
  - **Hadron production uncertainties can be reduced with NA61 kaon and replica target measurements**
  - **T2K is working to reduce the horn current uncertainty**

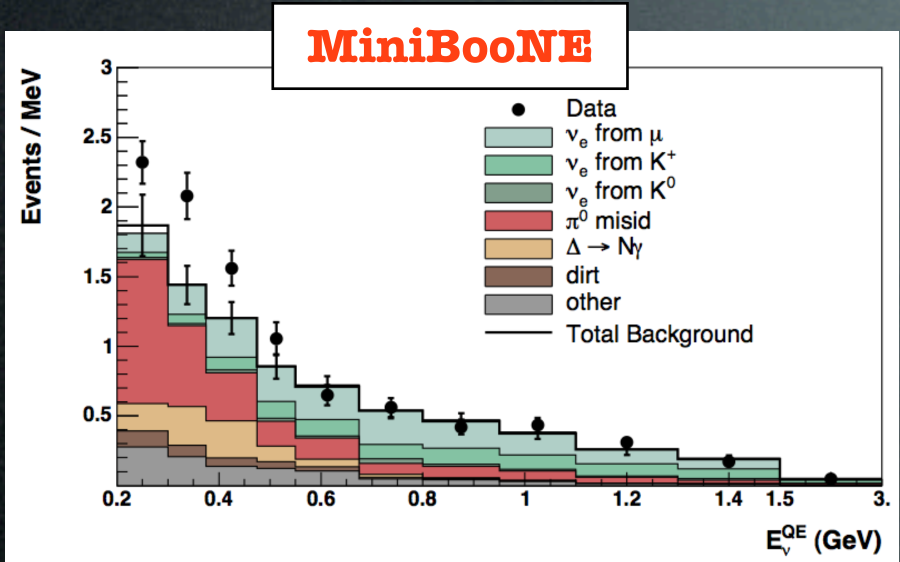


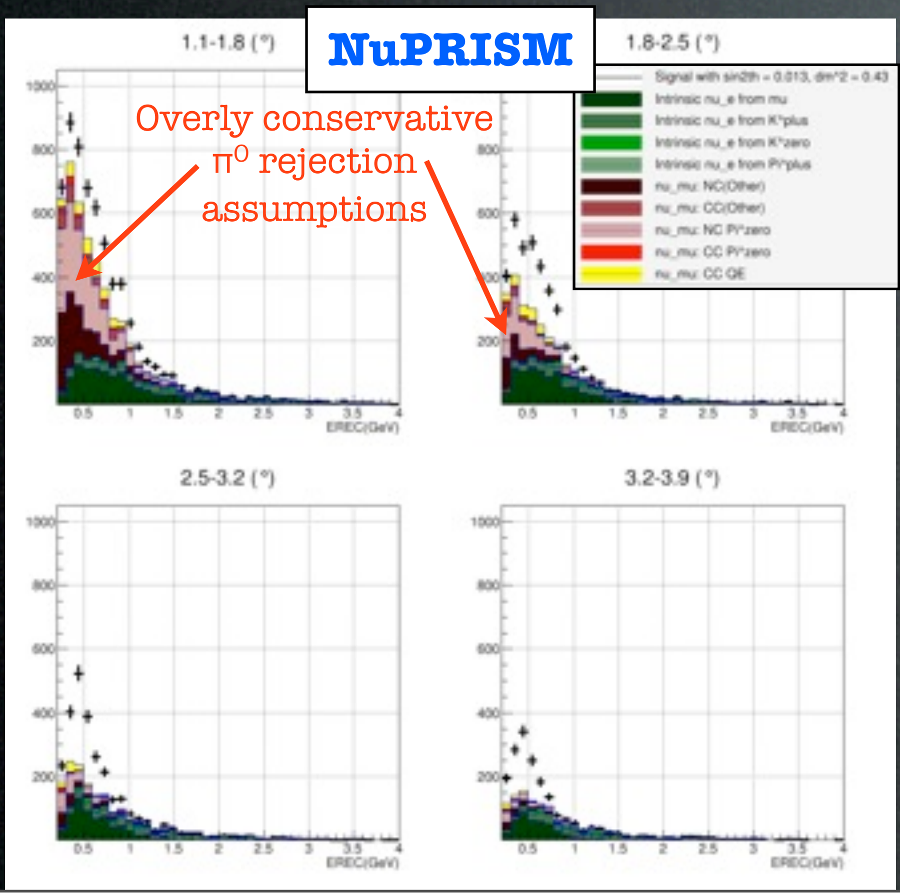


More Physics!

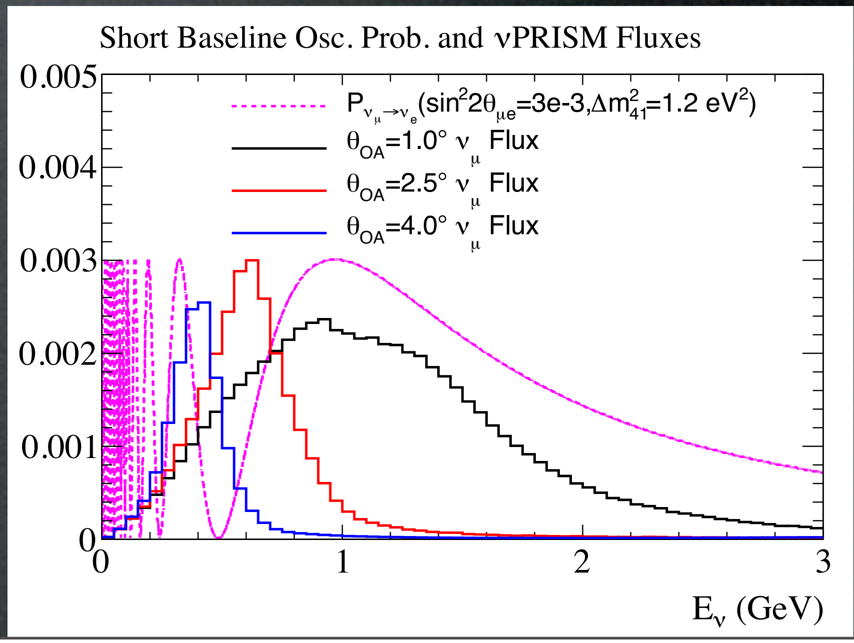
NuPRISM can do more than just improve long-baseline measurements

Sterile Neutrinos





- A multi-kton detector, ~1 km from a 600 MeV neutrino beam is well suited to confirm or refute the MiniBooNE/LSND event excesses
- NuPRISM has the additional benefit of continuously sampling a variety of L/E values
  - Oscillation signal and backgrounds vary differently vs off-axis angle
  - This provides an additional handle on many uncertain backgrounds (e.g. NC single-photon production)

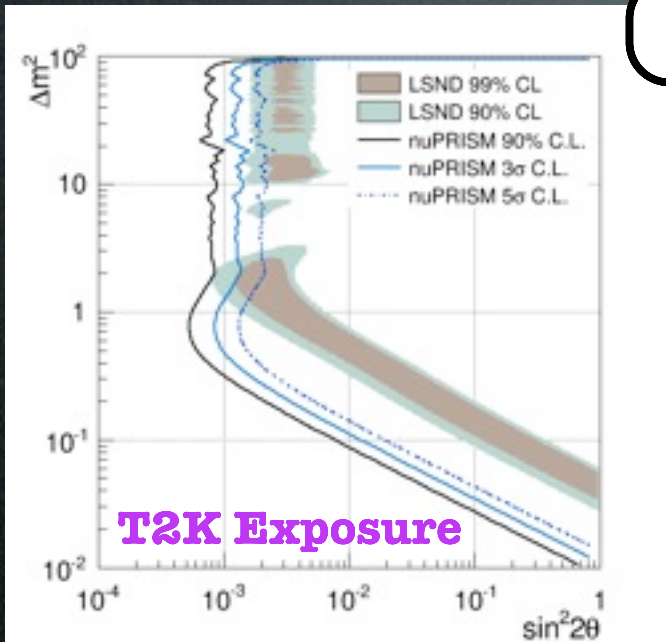


Sterile Neutrino Analysis

- To compute first sensitivities, make several conservative assumptions
- **No constraint from the existing near detector (ND280)**
    - Eventually, a powerful 2-detector constraint will be incorporated
- **No constraints on background processes**
    - NuPRISM should provide control samples for all of the major backgrounds to impose strong data-driven constraints
- **Assume Super-K detector efficiencies and resolutions**
    - NuPRISM has smaller phototubes, and should perform better closer to the wall (which is important, since the diameter is much smaller)
    - Significant increase in ν_e statistics is expected
- Since this analysis is still statistics limited, any additional running (T2K2 and/or Hyper-K) will improve the sensitivity

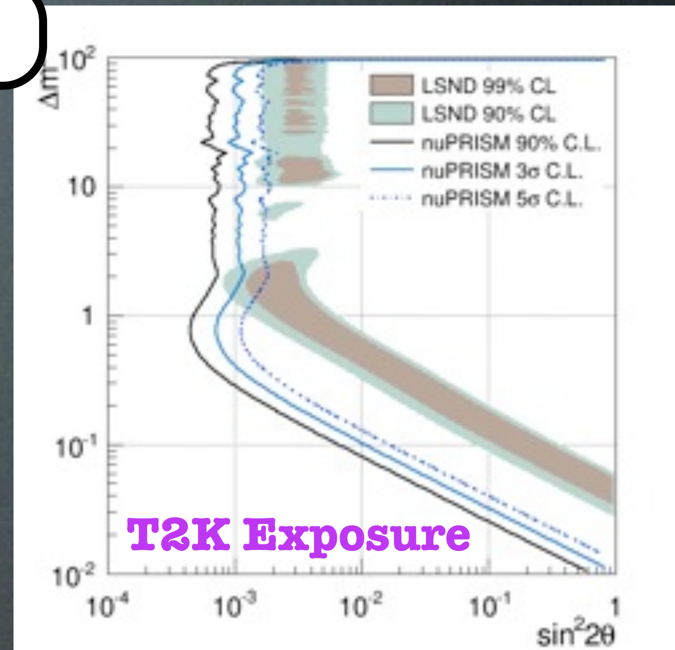
Current Sterile-ν Sensitivities

NuPRISM

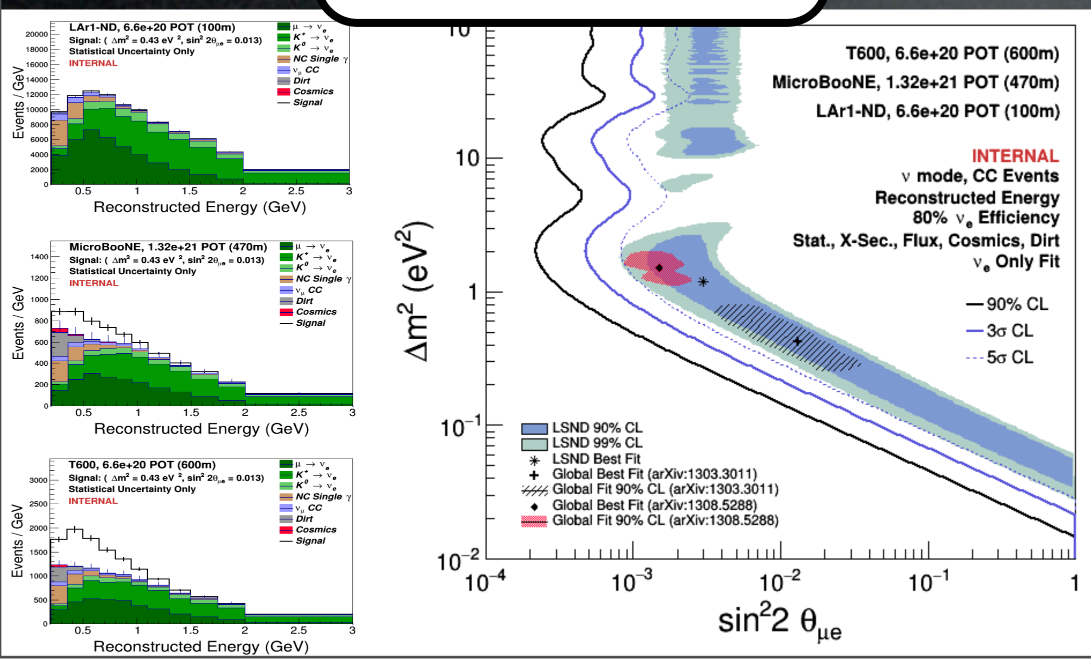


30% reduction in π^0 background or π^0 uncertainty

Should be easily achievable



Fermilab SBN

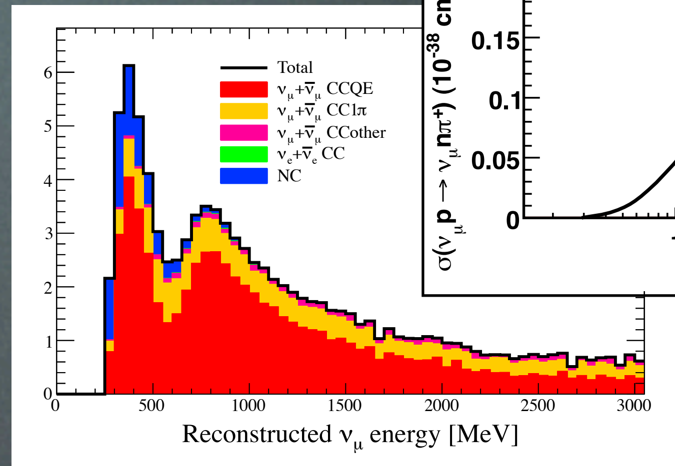


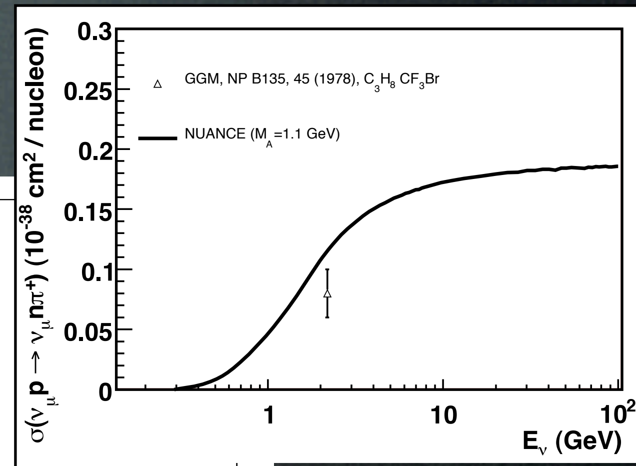
- Much of the LSND allowed region is already excluded at 3-5σ
  - Much better limits expected as the analysis improves (or with higher statistics)
- Current sensitivity is comparable to Fermilab short-baseline program
  - More importantly, Fermilab SBN has less power to rule out background explanations than NuPRISM

ν Cross Section Measurements

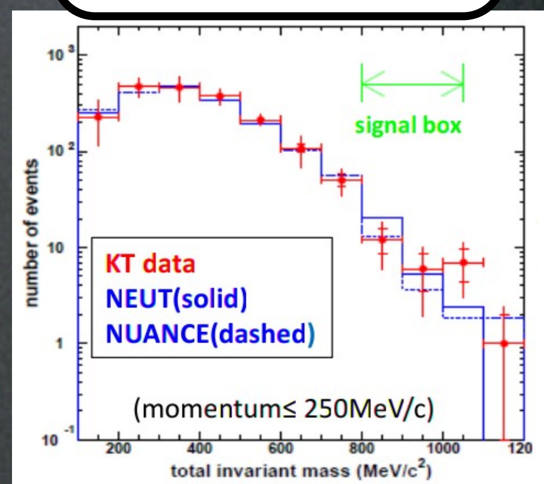
- T2K ν_μ disappearance is subject to large NCπ^+ uncertainties
    - 1 existing measurement
    - νPRISM can place a strong constraint on this process vs E_ν
- NuPRISM is an ideal setup to measure proton decay backgrounds
    - Repeat $p \rightarrow e^+\pi^0$ background measurement from K2K 1 kton detector
    - 50% of the $p \rightarrow K^+\nu$ background is from ν-induced K+ production
        - Production rate has large uncertainties
- Hyper-K proton decay measurements are background limited, so these measurements are crucial

NCπ^+ at T2K



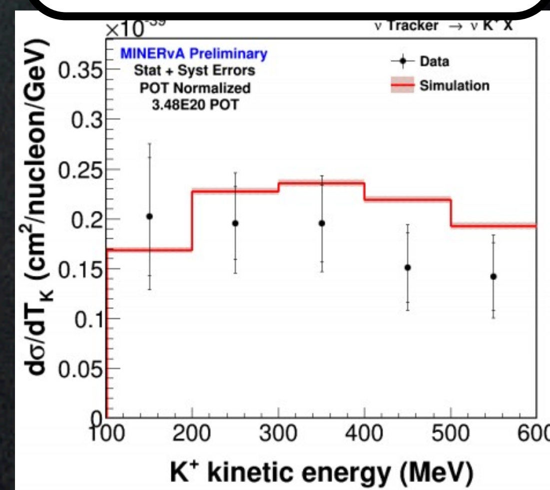


K2K $e^+\pi^0$ Bkgd Measurement



$$N(\mathrm{Mtyr}^{-1}) = 1.63^{+0.42}_{-0.33}(\mathrm{stat})^{+0.45}_{-0.51}(\mathrm{syst}).$$

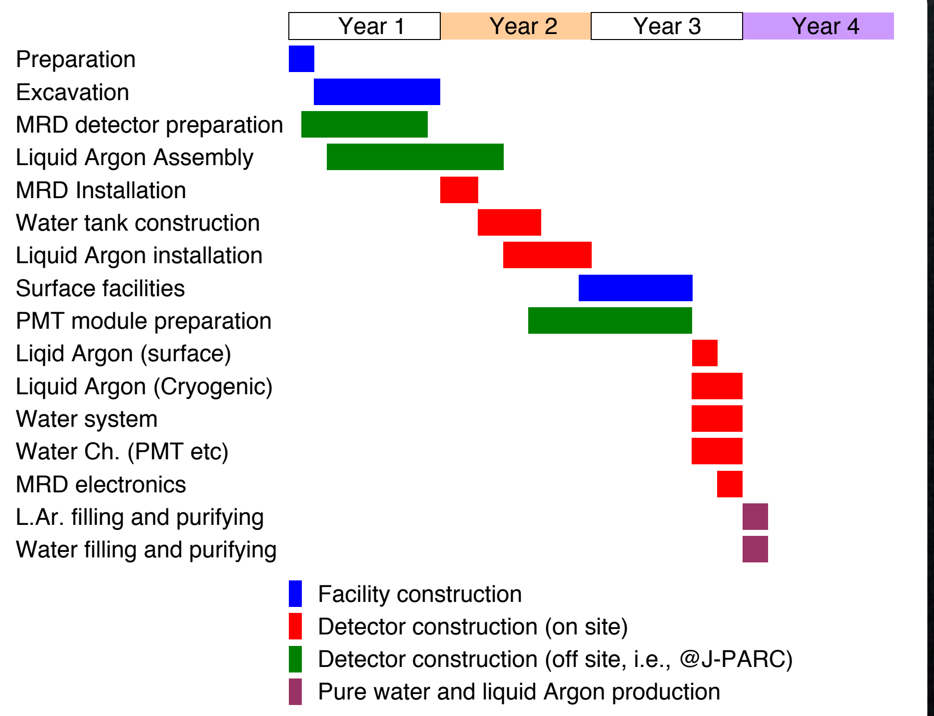
MINERvA K^+ Prod. Measurement

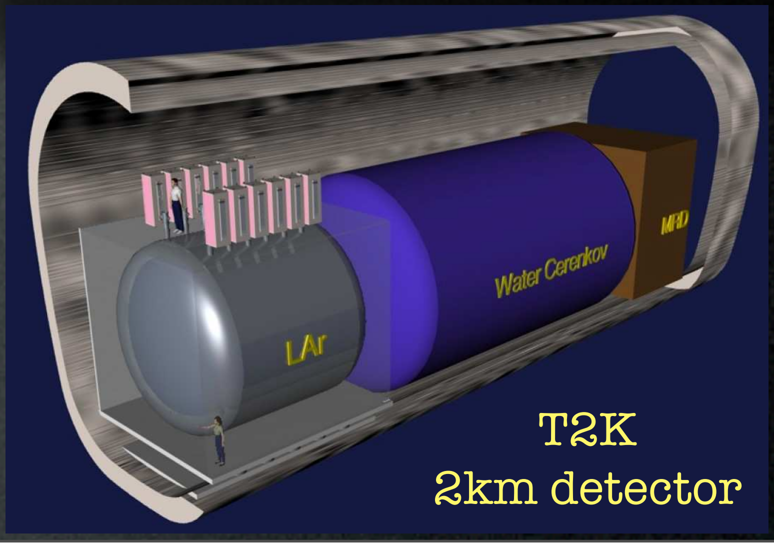


Timescales

- Water Cherenkov construction was studied for the T2K 2 km detector proposed in 2005
- NuPRISM construction time is faster
  - Same pit depth as the 2km detector, but no excavation of a large cavern at the bottom of the pit
  - Smaller instrumented volume
  - No MRD or LAr detector
- < 3 year timescale from ground breaking to data taking
- Goal is to start data taking soon after the J-PARC 750kW - 1 MW beam upgrade (2019)
  - 75% of the T2K extended run POT will be taken after the beam upgrade

Old T2K 2 km Schedule





Current Status

- Full proposal was review at the J-PARC PAC in January, 2016
- PAC Response: “In summary, NuPRISM is an excellent proposal. However, as already stressed in the previous PAC meeting, this proposal is intimately related to the extension of the T2K program, for which only an EOI has been submitted. Given the physics interest of NuPRISM, the PAC strongly encourages the continuation of R&D studies in close collaboration with the proponents of the T2K-II program. The PAC recommends that NuPRISM be considered for Stage-1 status following an evaluation of the T2K-II proposal.”
- The T2K extended run proposal will be submitted for the July, 2016 PAC, and we are proposing concurrent approval of NuPRISM at that meeting

Proposal for the NuPRISM Experiment in the J-PARC Neutrino Beamline

S. Bhadra,[28] A. Blondel,[4] S. Bordoni,[7] A. Bravar,[4] C. Bronner,[10] R.G. Calland,[10] J. Caravaca Rodríguez,[7] M. Dziewiecki,[27] M. Ericson,[12,3] T. Feusels,[1] G.A. Fiorentini Aguirre,[28] M. Friend,[6,*] L. Haegel,[4] M. Hartz,[10,26] R. Henderson,[26] T. Ishida,[6,*] M. Ishitsuka,[23] C.K. Jung,[14,†] A.C. Kaboth,[8] H. Kakuno,[24] H. Kamano,[16] A. Konaka,[26] Y. Kudenko,[9,‡] R. Kurjata,[27] M. Kuze,[23] T. Lindner,[26] K. Mahn,[13] J.F. Martin,[25] M. Martini,[5] J. Marzec,[27] K.S. McFarland,[18] S. Nakayama,[21,†] T. Nakaya,[11,10] S. Nakamura,[15] Y. Nishimura,[22] A. Rychter,[27] F. Sánchez,[7] T. Sato,[15] M. Scott,[26] T. Sekiguchi,[6,*] T. Shima,[16] M. Shiozawa,[21,10] T. Sumiyoshi,[24] R. Tacik,[17,26] H.K. Tanaka,[21,†] H.A. Tanaka,[1,§] S. Tobayama,[1] M. Vagins,[10,2] C. Vilela,[14] J. Vo,[7] D. Wark,[19,8] M.O. Wascko,[8] M.J. Wilking,[14] S. Yen,[26] M. Yokoyama,[20,†] and M. Ziembicki[27]
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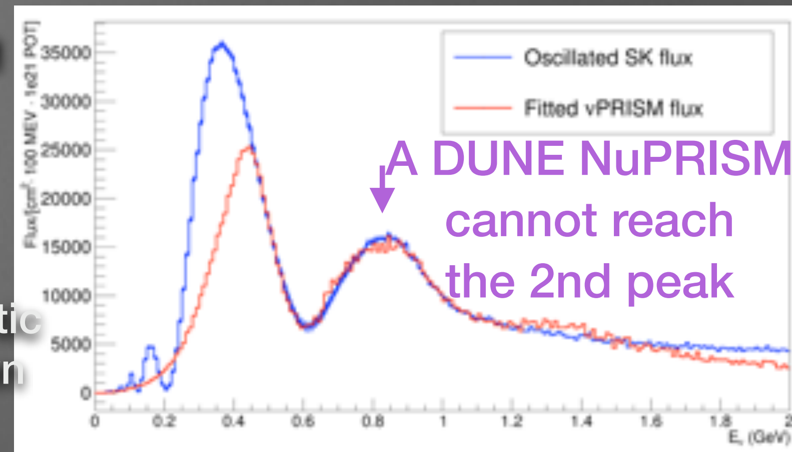
(Dated: June 16, 2015)

NuPRISM for DUNE?

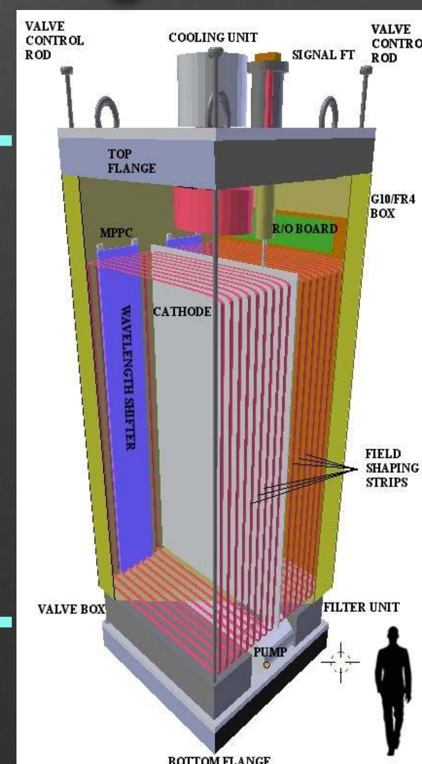
- DUNE configuration presents some **challenges for NuPRISM**
    - **On-axis beam**: no longer able to sample energies below <u>and above</u> the 1st oscillation maximum
        - However, it is still possible to produce mono-energetic beams up to the 1st maximum to measure feed-down
        - NuPRISM is very well suited to constrain the 2nd oscillation maximum
    - **Neutrinos from kaon decay** can make the cancelation of the high energy tails in the linear combinations more difficult



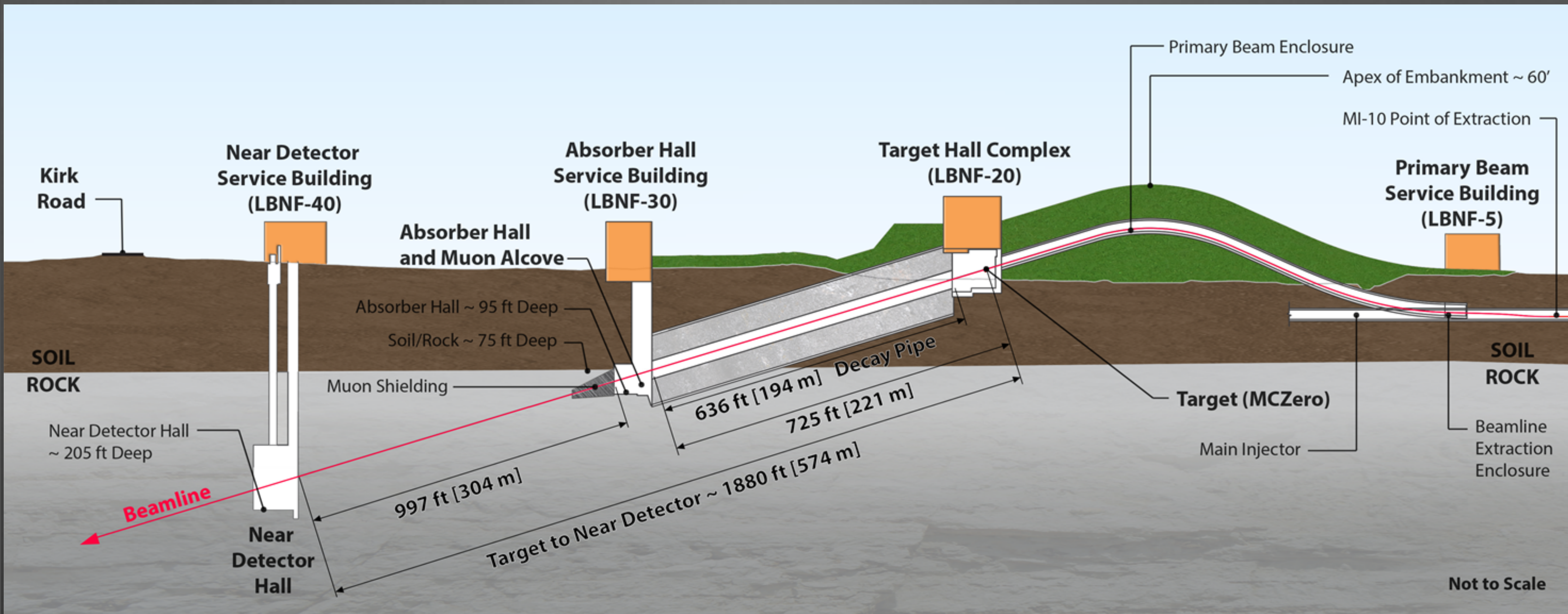
- **Detector technology**
    - Principle of NuPRISM is to measure the "exact" response of the far detector for a known incident neutrino energy
        - Near detector should be as similar as possible to the far detector (Ar target, 4π coverage, hadronic containment?, etc.)
    - **LAr TPC** is an obvious technology choice (e.g. ArgonCube)
        - However, if neutrons can not be well measured in a high rate environment, a **high-pressure gas TPC** may also work

ArgonCube

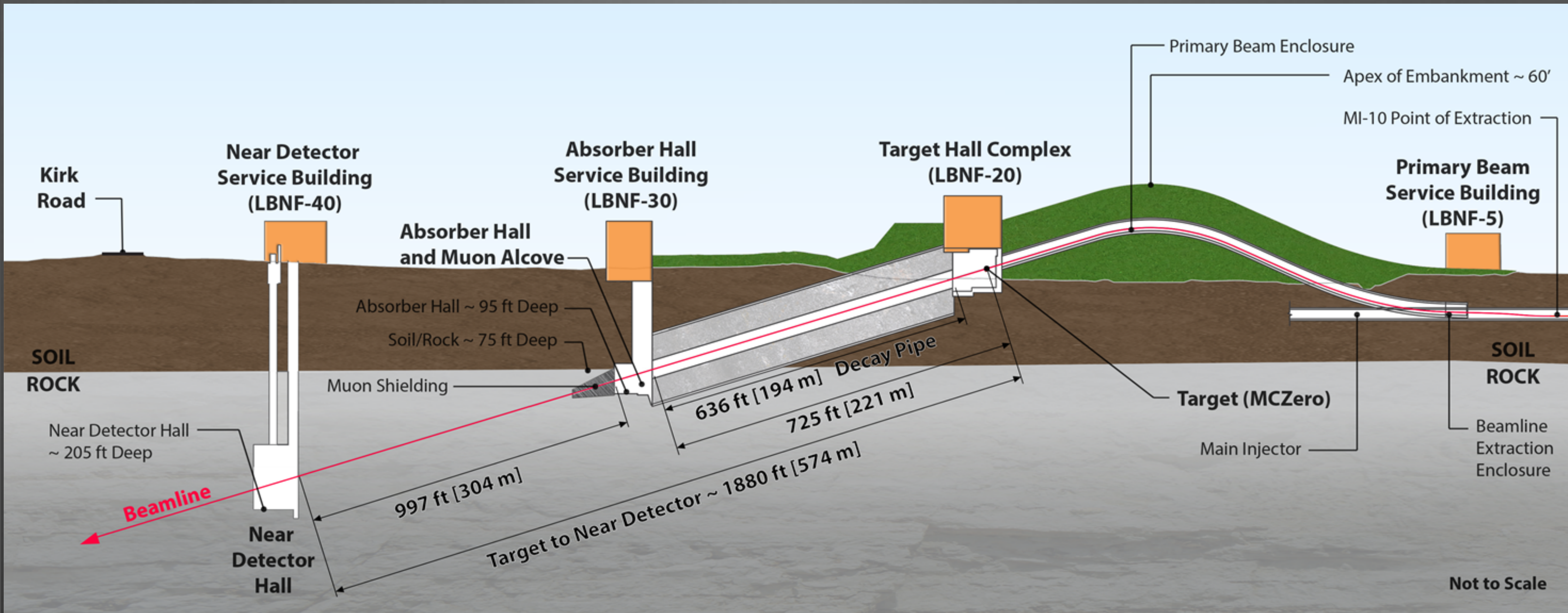
9 m tall



DUNE-PRISM Configuration

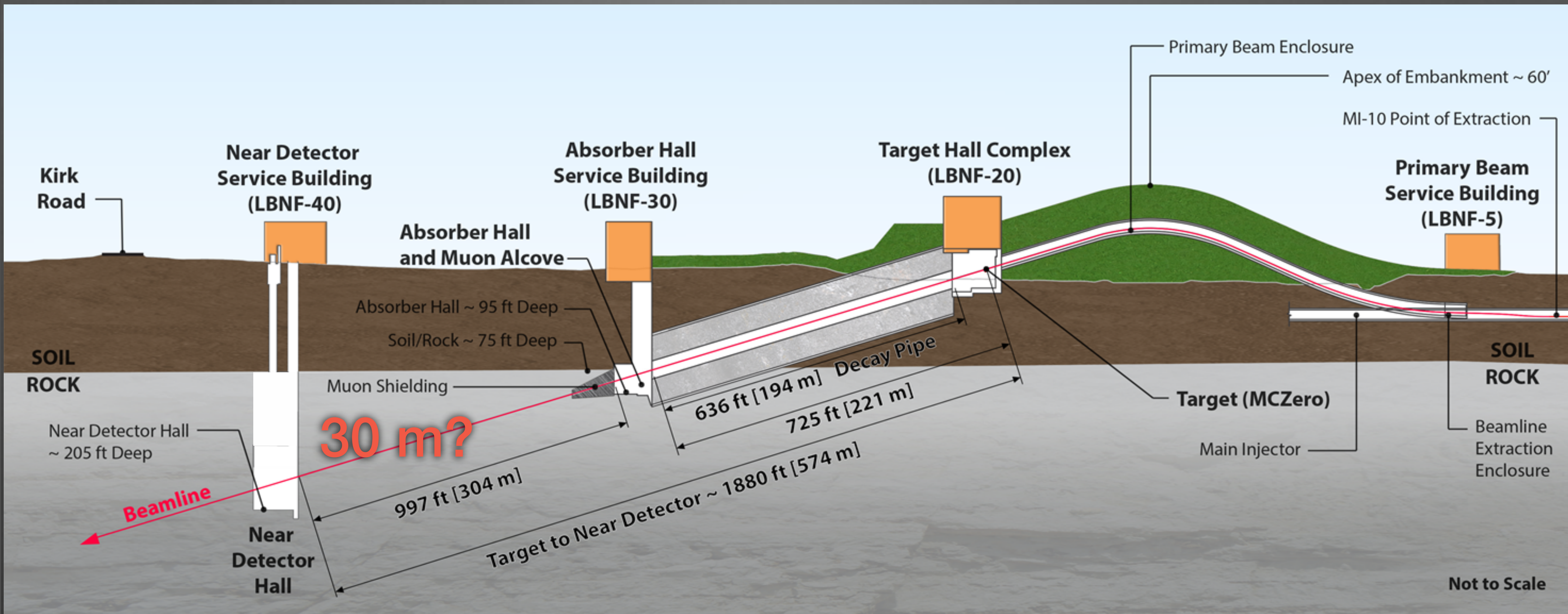


DUNE-PRISM Configuration



- The floor of the current near detector hall is 62.5 m below the surface
  - Ceiling can likely be raised for minimal additional cost

DUNE-PRISM Configuration



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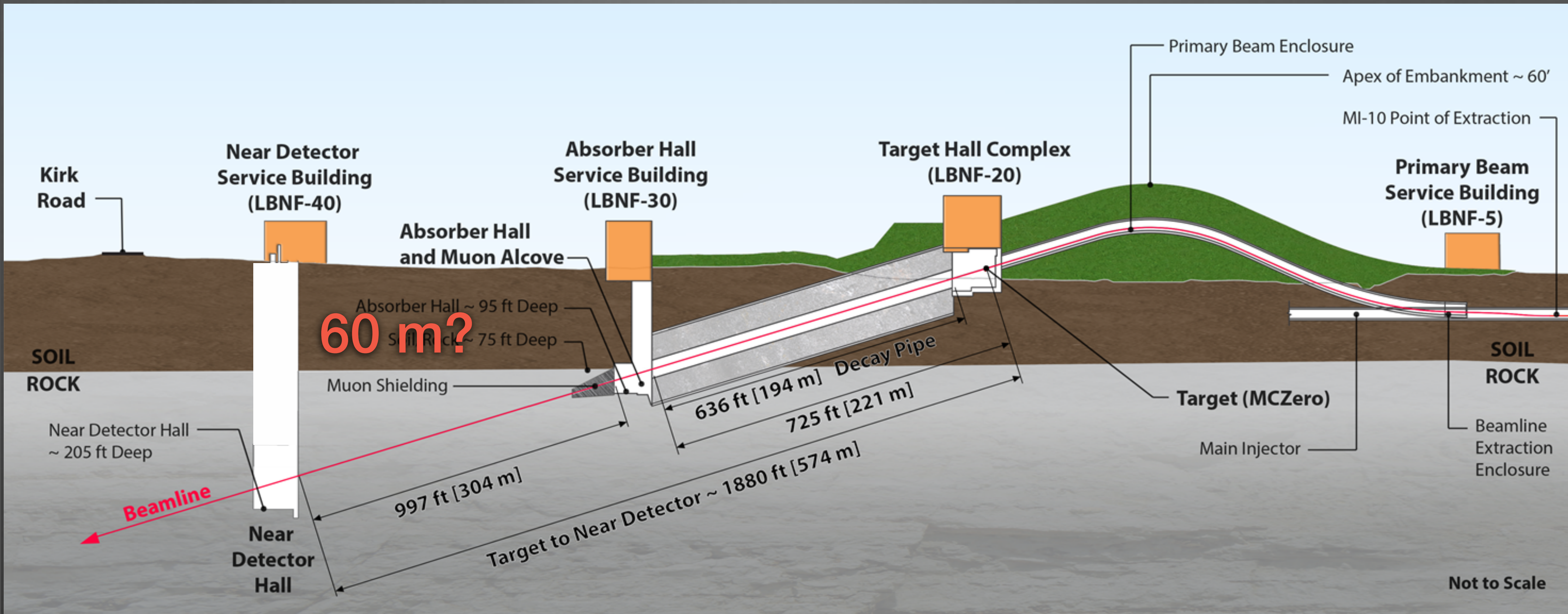
DUNE-PRISM Configuration



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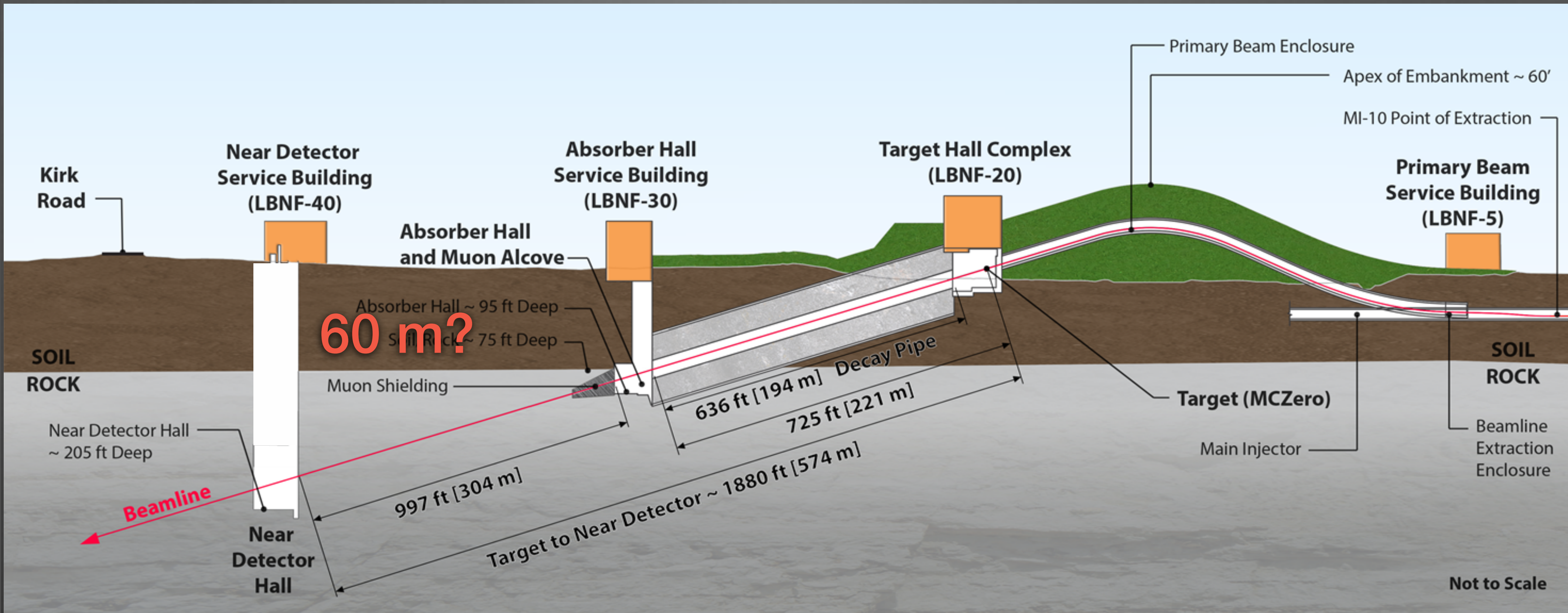
DUNE-PRISM Configuration

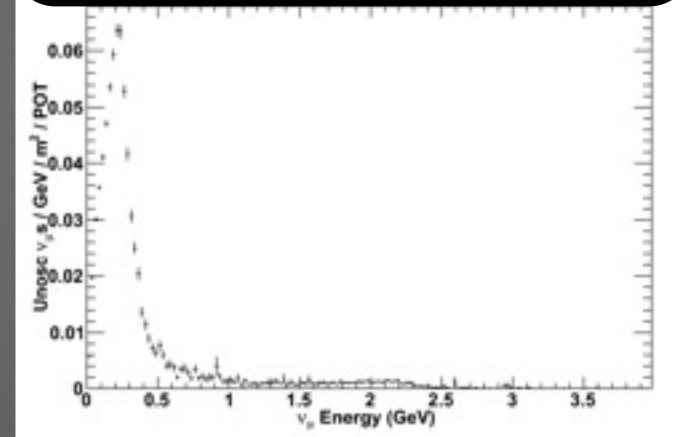


- The floor of the current near detector hall is 62.5 m below the surface
  - Ceiling can likely be raised for minimal additional cost
  - Excavating a pit to the surface provides up to 6.25° (109 mrad) in off-axis angle

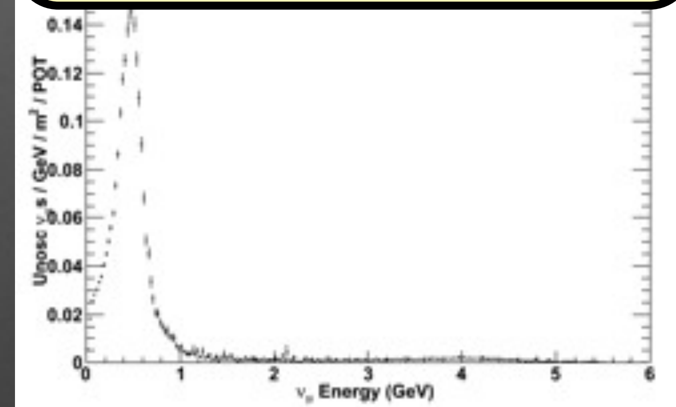
DUNE Flux Fits

- Initial NuPRISM fits have been performed using the DUNE flux
- The following is an initial (crude) feasibility study
  - Many improvements to be made
    - Higher beam MC stats
    - Fits of $\Phi^{*}E_{\nu}$
    - More careful analysis of kaon peak cancelation
    - etc.
- However, even at this early stage, there is a strong indication that applying the NuPRISM concept to DUNE is possible (next slides)

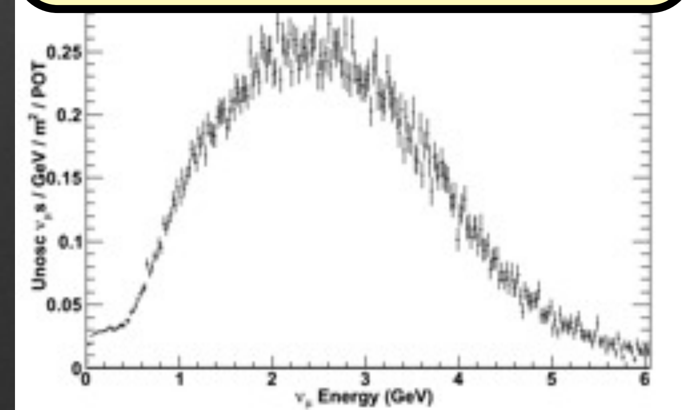
6.0° (105 mrad) Off-axis



2.9° (50 mrad) Off-axis

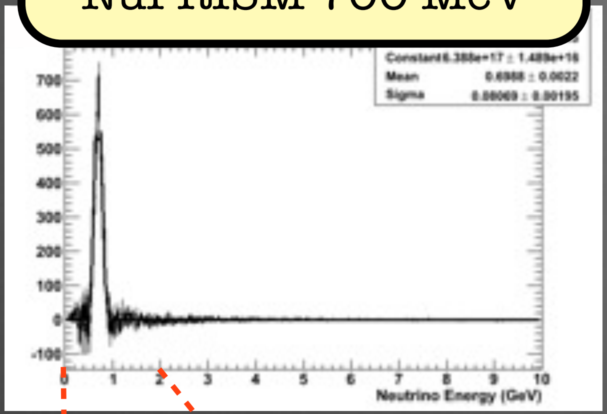


0° (0 mrad) Off-axis

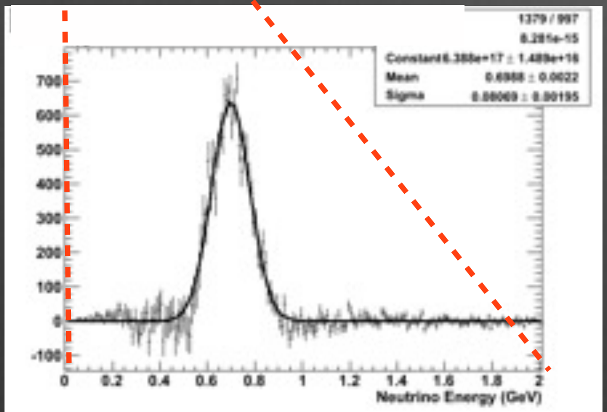


NuPRISM vs 60 m DUNE-PRISM (mid-E_ν)

NuPRISM 700 MeV



zoom

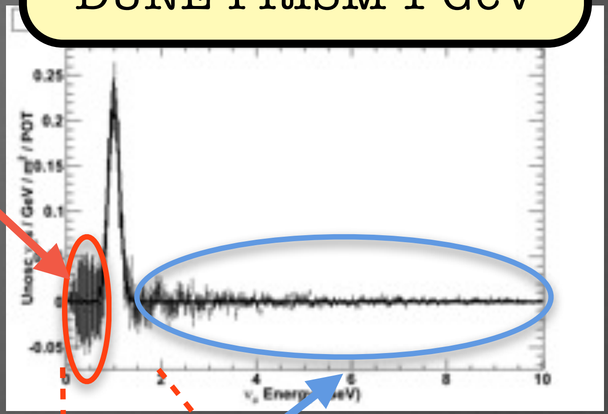


Larger errors at low E are due to more off-axis slices & no flux-weight smoothing

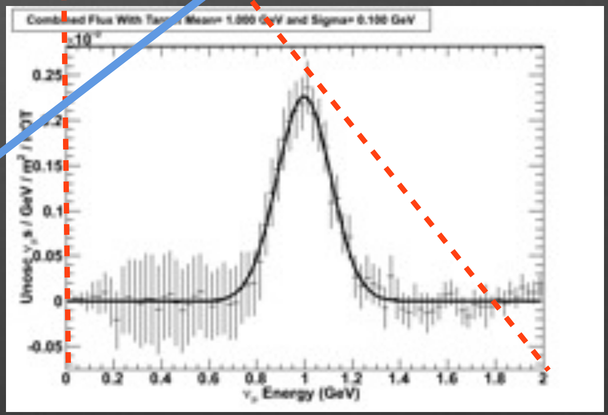
Easy to fix

Good cancelation of high energy flux tail

DUNE-PRISM 1 GeV



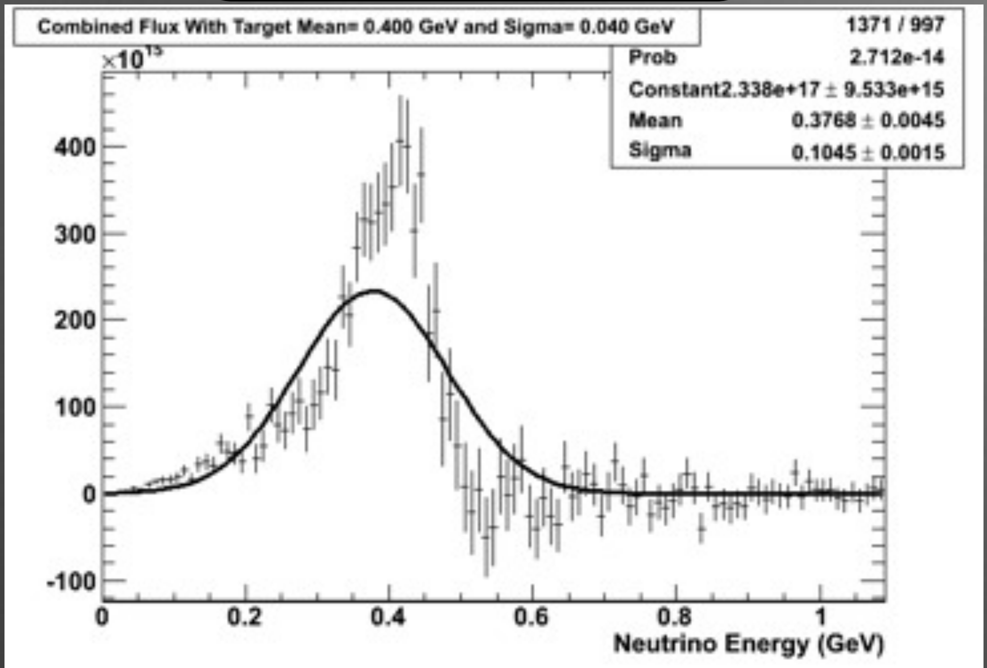
zoom



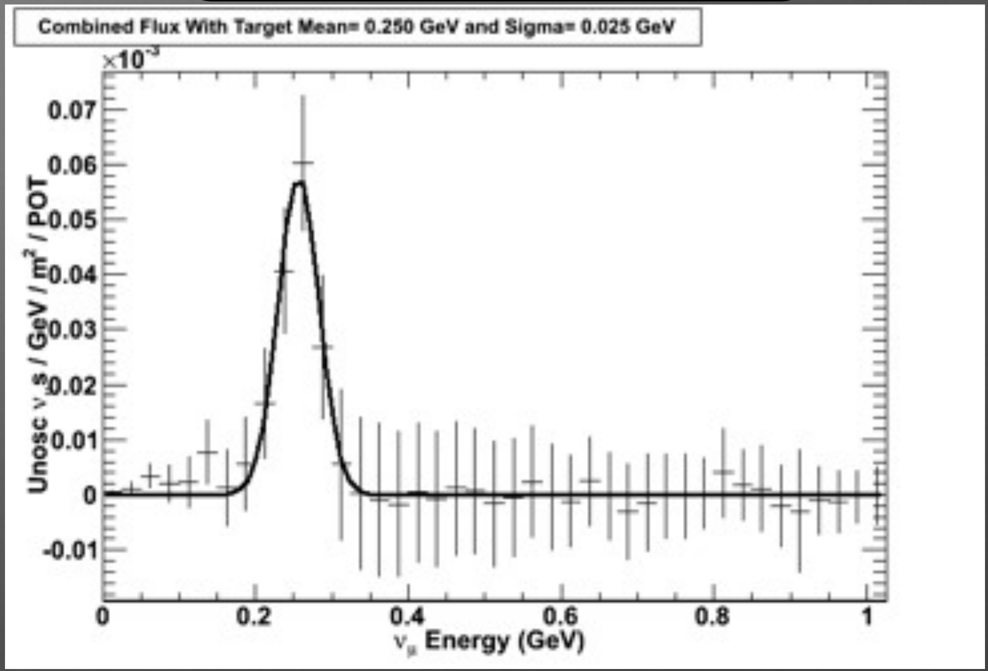
- Similar fit performance for the two detectors

NuPRISM vs 60 m DUNE-PRISM (low-E_ν)

NuPRISM 0.4 GeV



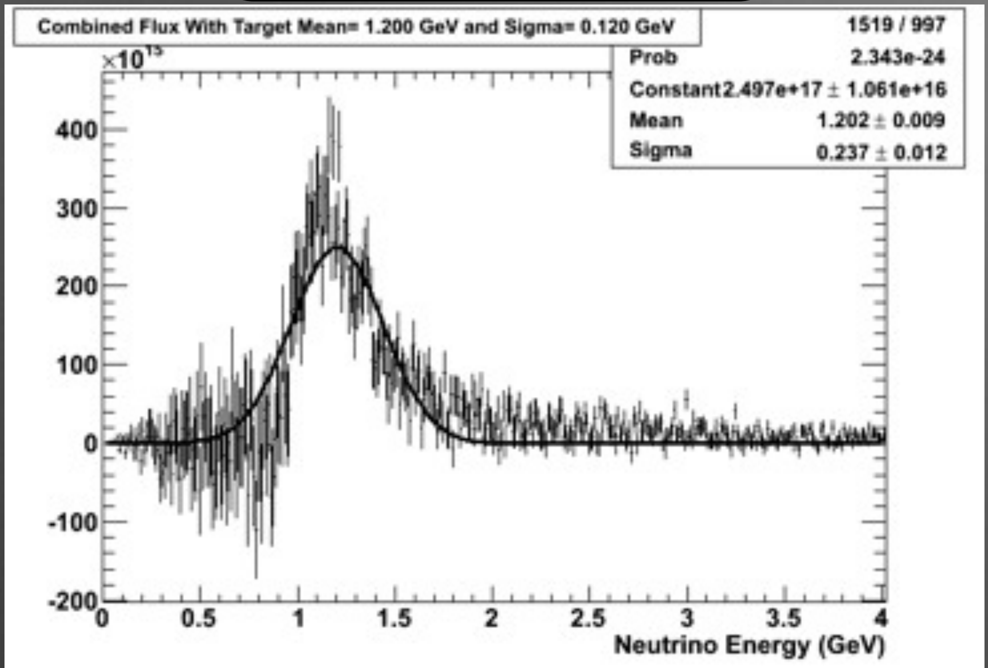
DUNE-PRISM 0.25 GeV



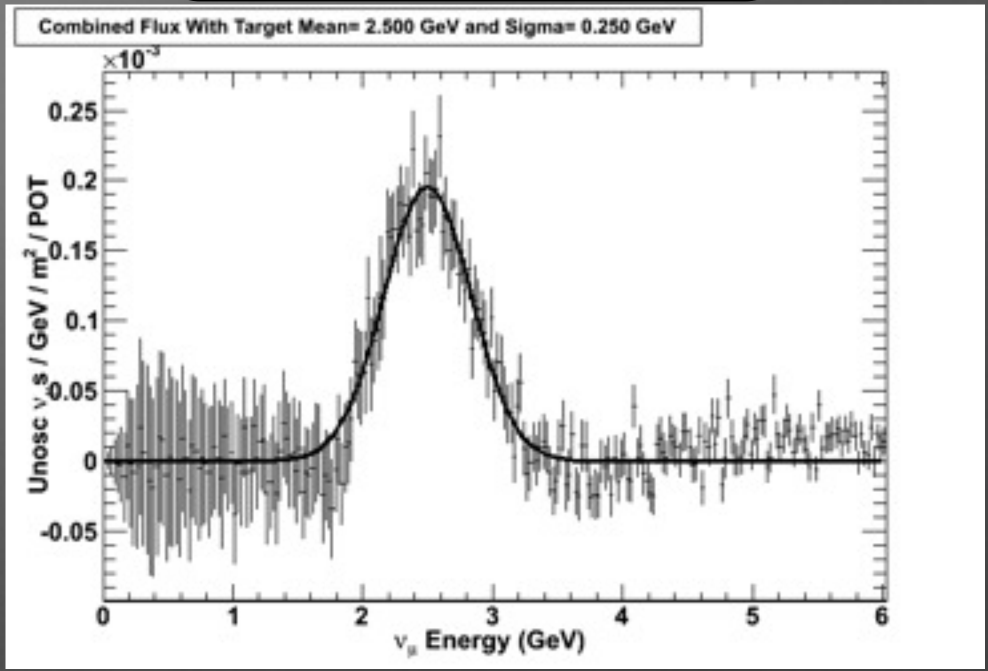
- NuPRISM fits begin to degrade at 400 MeV
  - This is the where the most off-axis flux (4°) peaks
- 60 m DUNE-PRISM fits work well down to 250 MeV
  - This is well below the position of the 2nd oscillation maximum

NuPRISM vs 60 m DUNE-PRISM (high-E_ν)

NuPRISM 1.2 GeV



DUNE-PRISM 2.5 GeV



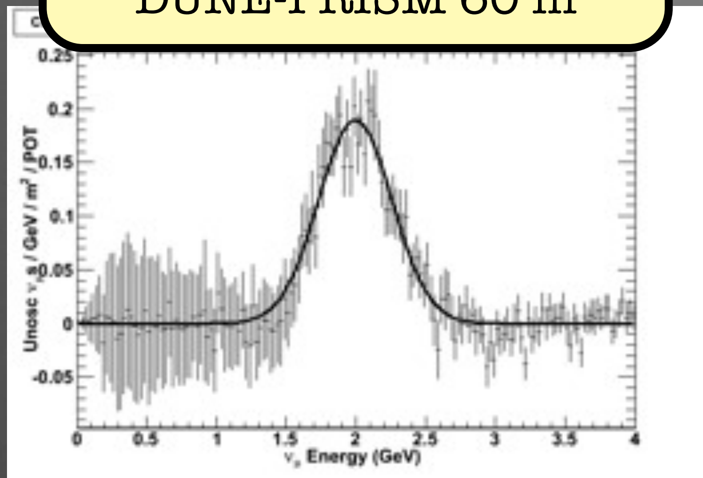
- NuPRISM fits begin to degrade around 1.2 GeV (the on-axis flux peak)
    - This is well above the oscillation maximum (700 MeV)
- 60 m DUNE-PRISM can reach roughly 2.5 GeV
    - Unfortunately, this is near the center of the oscillation maximum
    - It is still very valuable to calibrate detector response from 0 to 2.5 GeV

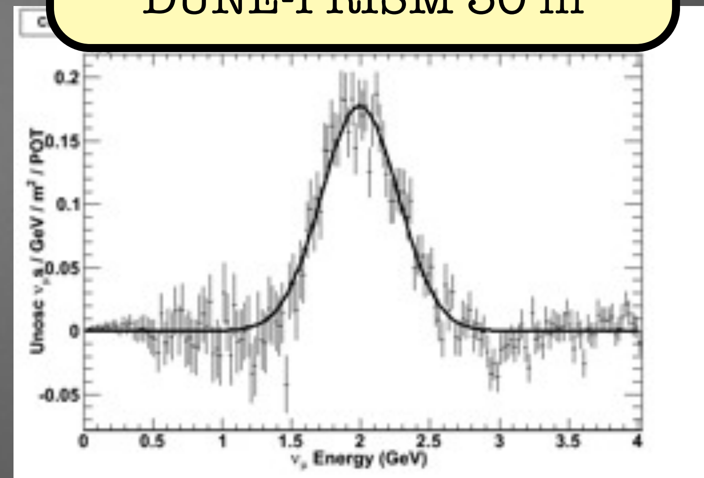
30 m vs 60 m DUNE-PRISM

DUNE-PRISM 60 m

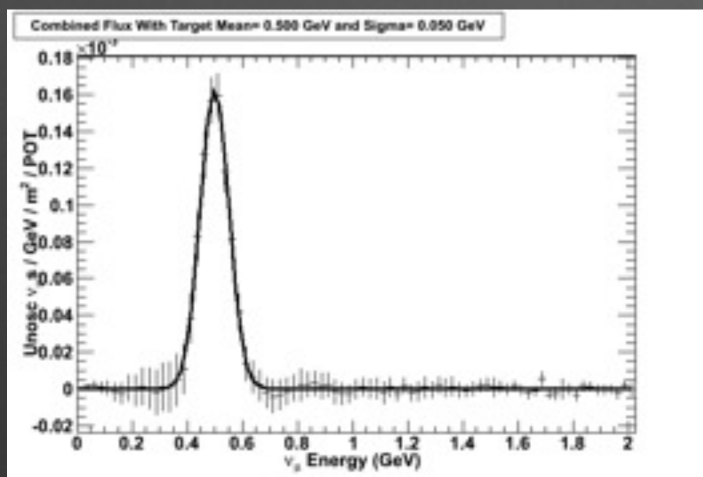
DUNE-PRISM 30 m

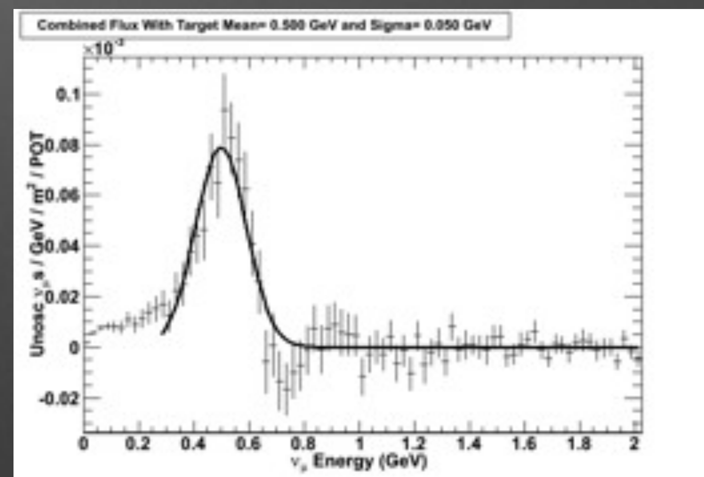
2.0 GeV





0.5 GeV

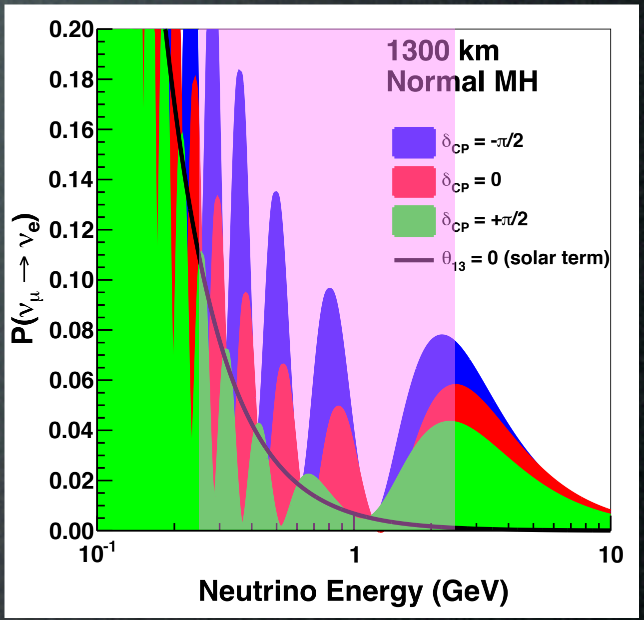




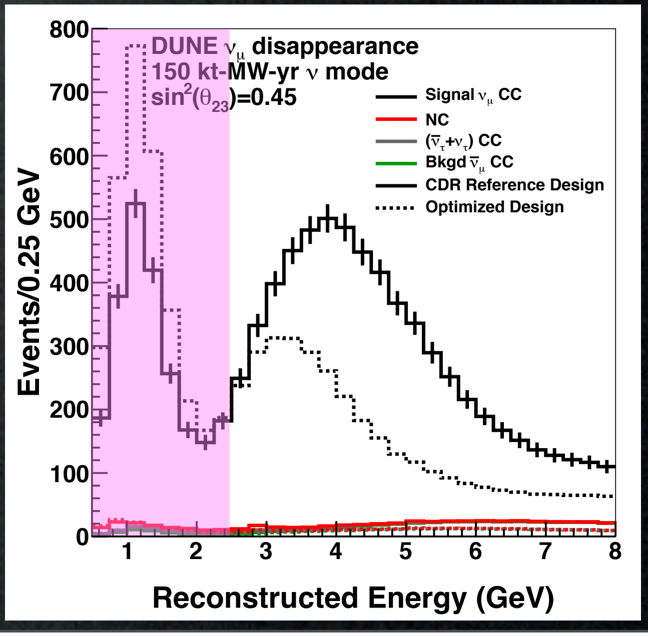
- High energy fits are unaffected (recall low-E “noise” is just due to more slices)
- Low energy fits no longer work
  - Lower off-axis range = higher low-E threshold

DUNE-PRISM Summary

- In the current DUNE configuration, DUNE-PRISM cannot fully cover the 1st oscillation maximum
    - The 2nd oscillation maximum is very well covered
- Increasing the beam energy and moving the beam slightly off-axis would improve the situation
    - Current optimization studies disfavor off-axis beams, but this could change as more detailed systematics are incorporated into the analysis
- Even in the current configuration, DUNE-PRISM would allow for a **precise measurement** of **$E_\nu(p_\mu, \theta_\mu, E_{hadronic})$** for $E_\nu < 2.5$ GeV
    - This is a particularly important region where CCQE, CCπ, and DIS interactions all contribute

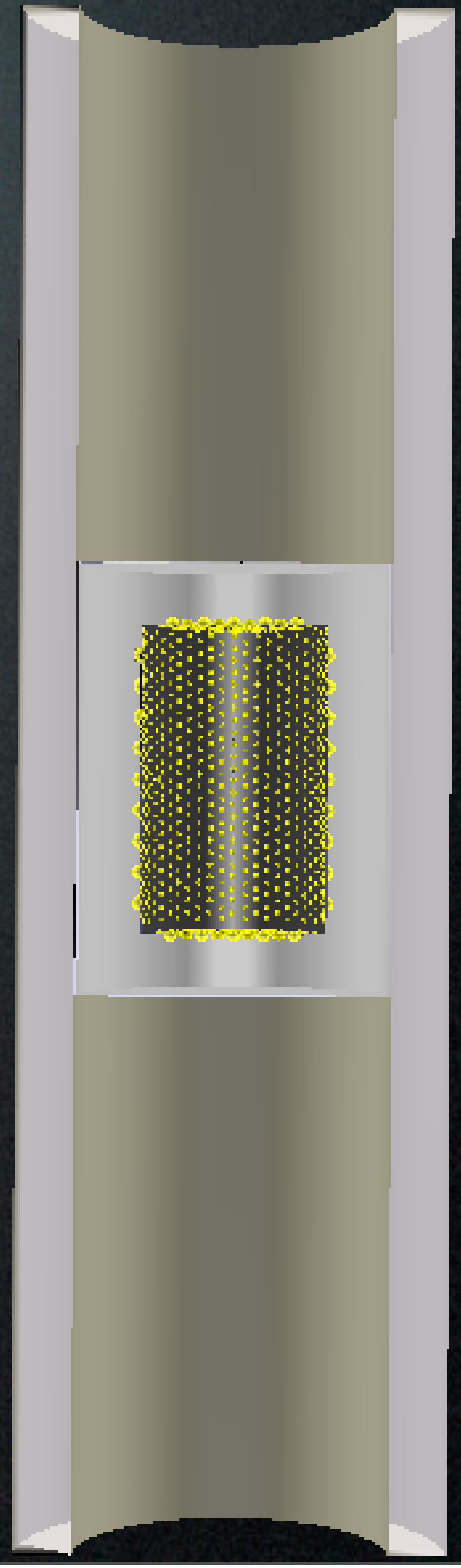


NuPRISM Range



Summary

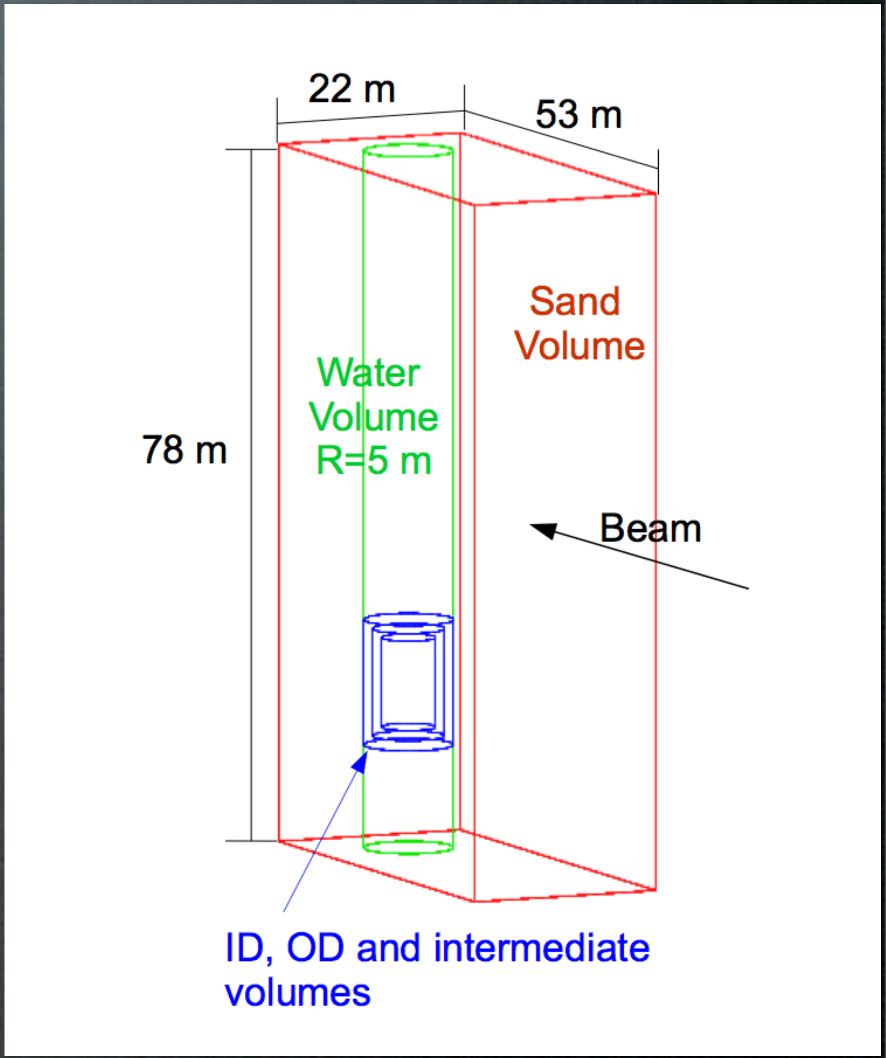
- We are entering an era where the largest uncertainties in neutrino oscillation experiments will be determined by poorly understood models
    - NuPRISM provides an **experimental solution** for the uncertainties in **neutrino-nucleus interactions**
- NuPRISM will produce a wide variety of other interesting measurements
    - A unique **sterile neutrino** search
    - **Nuclear physics** from mono-energetic beams
    - A wide variety of **unique cross section measurements** and model constraints
- These physics goals can be achieved with half of the total POT for an extended T2K run
- NuPRISM can supply an exciting physics program that bridges the gap between T2K and Hyper-K
    - Similar to the Fermilab LAr short-baseline neutrino program
- The NuPRISM concept can be applied to any long-baseline neutrino experiment (e.g. DUNE)



Supplement

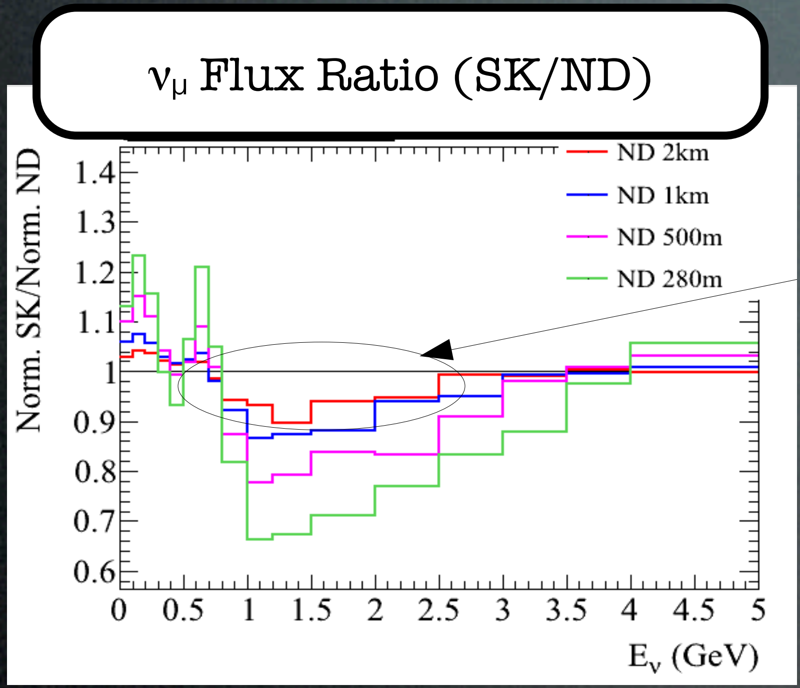
Event Pileup

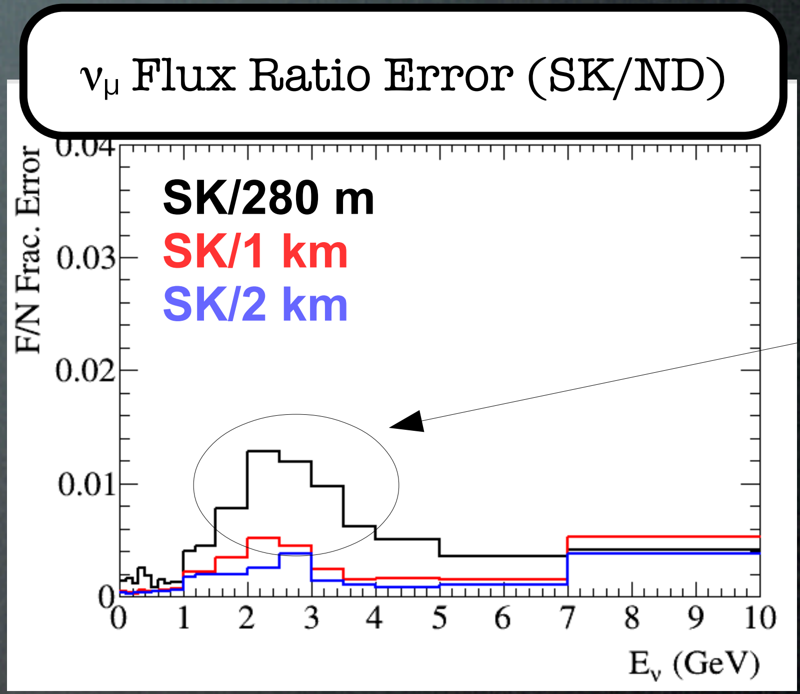
- Full GEANT4 simulation of water and surrounding sand
  - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **92%/26%/11% chance of OD light in a bunch at 1.3°/2.3°/3.3° degrees off axis**
  - Simple cut on OD light may be too crude
    - Can use the scintillator panels to tag entering particle locations
- **4.6%/1.7%/0.8% of bunches have ID activity from more than 1 interaction**
  - Use the reconstruction to either veto multiple vertices (or multiple rings), or just reconstruct each vertex
    - Significant advances in multi-ring reconstruction are now available



Pileup Rates at 1 km Look Acceptable

Detector Location: Energy Spectrum Ratio

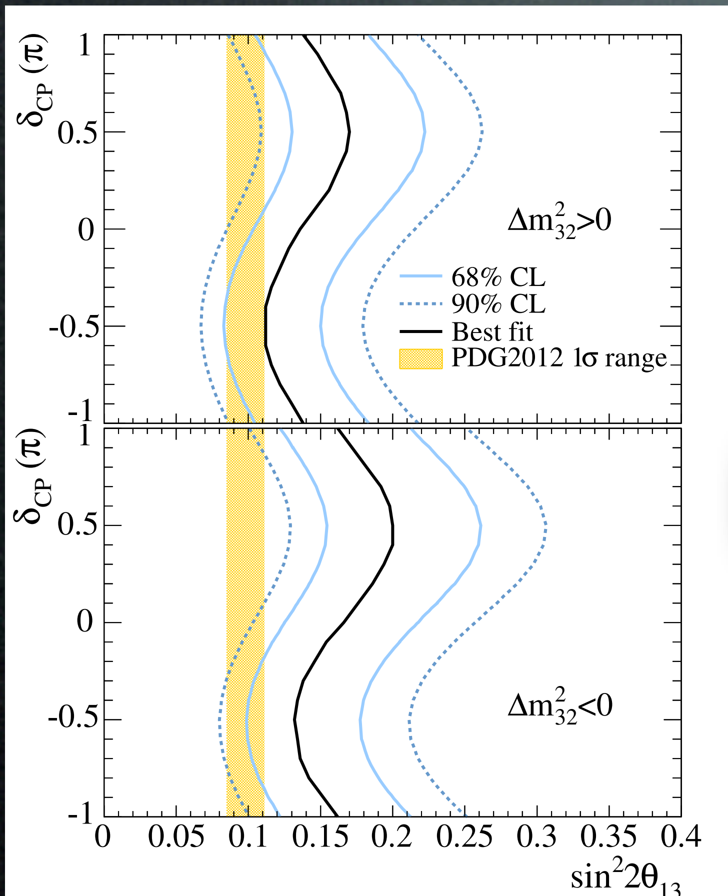




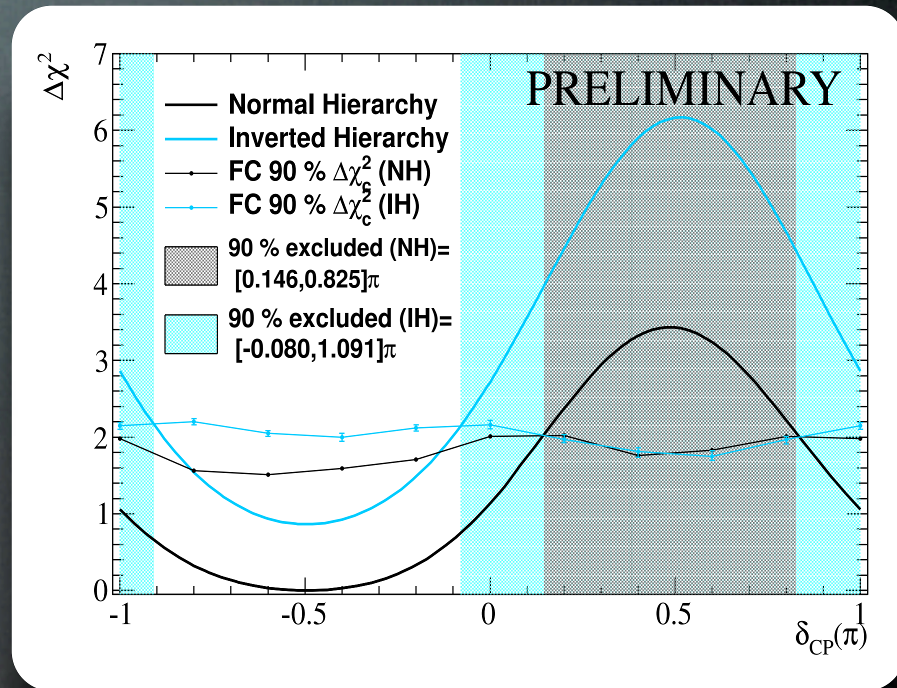
- At 280 m, the flux shape has 20-30% differences below 1 GeV
  - Uncertainty in the ratio is noticeably larger, but mostly above 1 GeV
- The difference between 1km and 2km is small in both shape and shape uncertainty

T2K ν_e Appearance Results

Observed 28 events (expected 21.6 ± 1.9 for $\sin^2 2\theta_{13}$=0.1, δ_{CP}=0)



7.5σ exclusion of θ_{13}=0

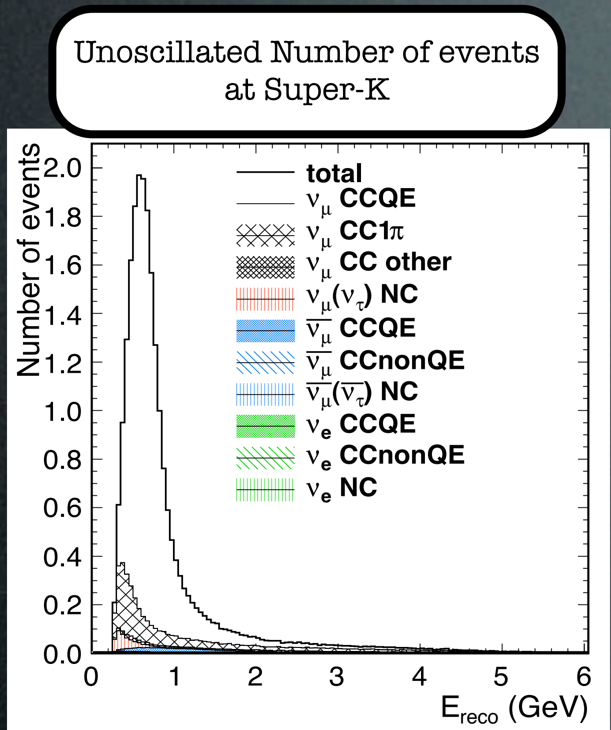


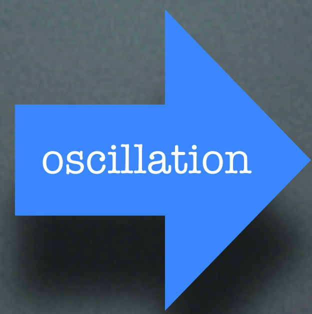
First ever observation (>5σ) of an explicit ν appearance channel

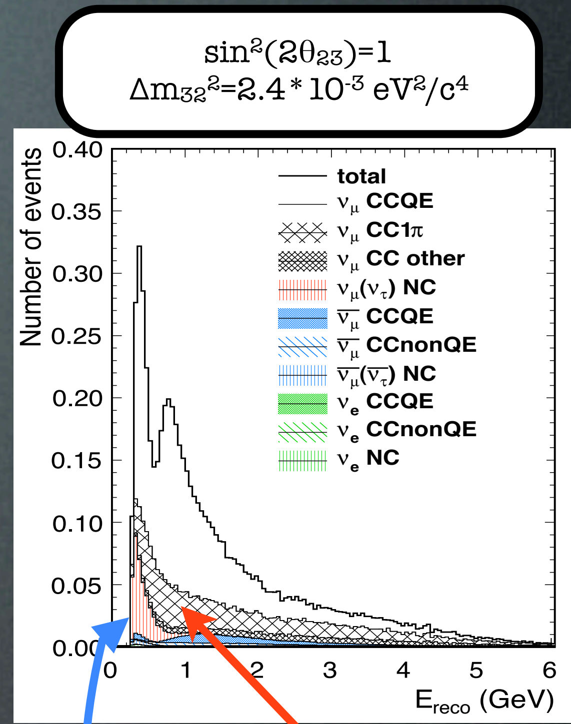
When combined with reactor θ_{13} measurements,

Significant regions of CP excluded at 90% C.L.

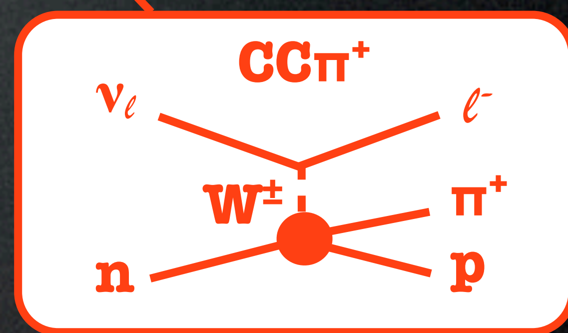
T2K ν_μ Disappearance

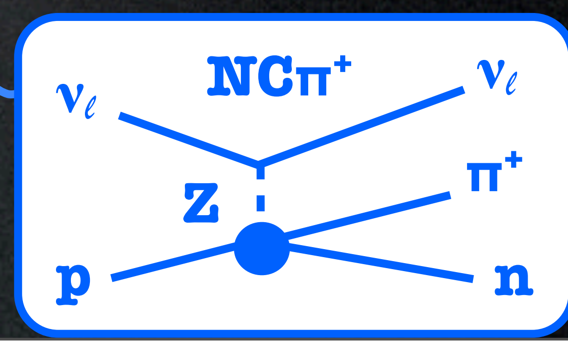






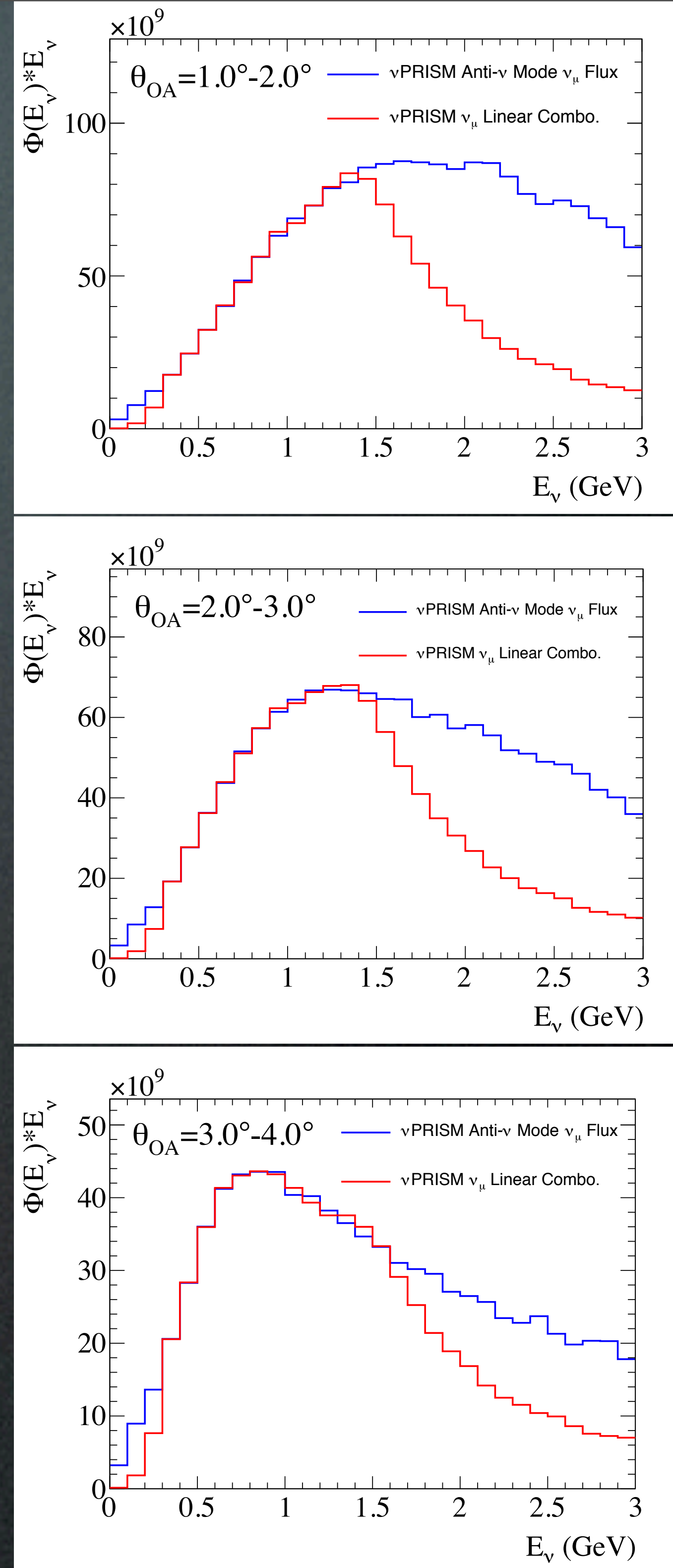
- Largest backgrounds are from CCπ^+ and NCπ^+
- **NCπ^+**: pion is misidentified as a muon
  - **Uncertainty on NCπ^+ is large (>100%)**
- **CCπ^+**: pion is unobserved
  - Neutrino energy is misreconstructed
  - Fills in the oscillation "dip" (big impact on θ_{23} measurement)





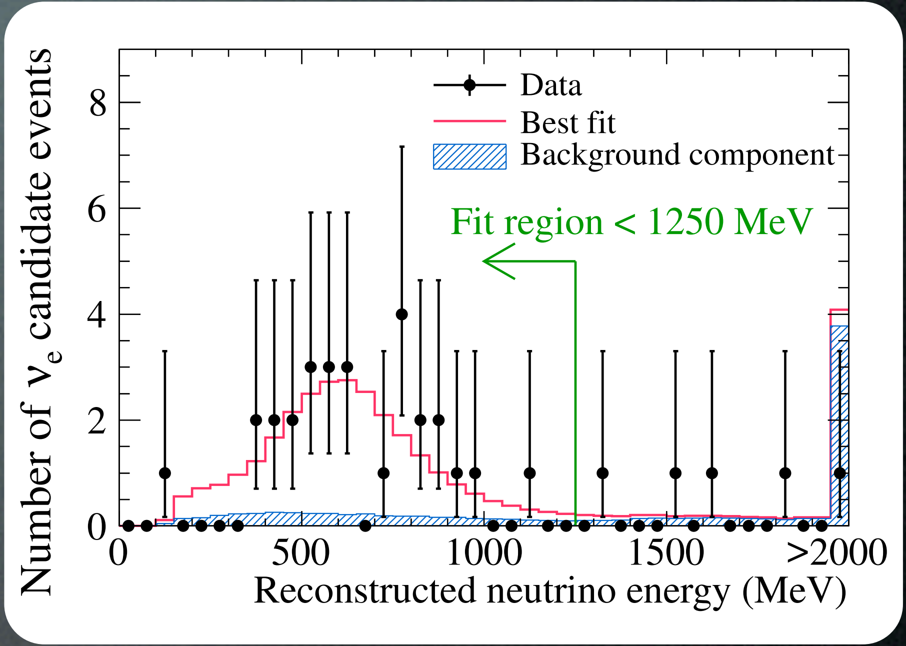
Anti-neutrinos

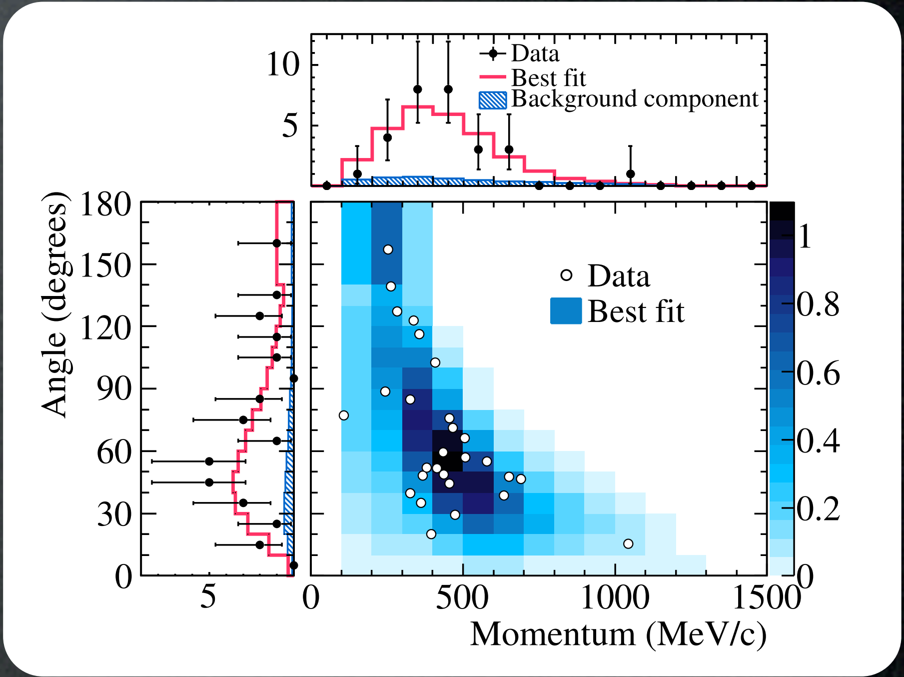
- T2K can switch between ν-mode and anti-ν-mode running by switching the beam focusing
- Anti-ν-mode analysis is the same as for neutrinos
  - Except with a much larger neutrino contamination
- Can use ν-mode ν_μ data to construct the ν_μ background in the anti-ν-mode anti-ν_μ data
- After subtracting neutrino background, standard nuPRISM oscillation analyses can be applied to anti-neutrinos



ν_e Appearance Analysis

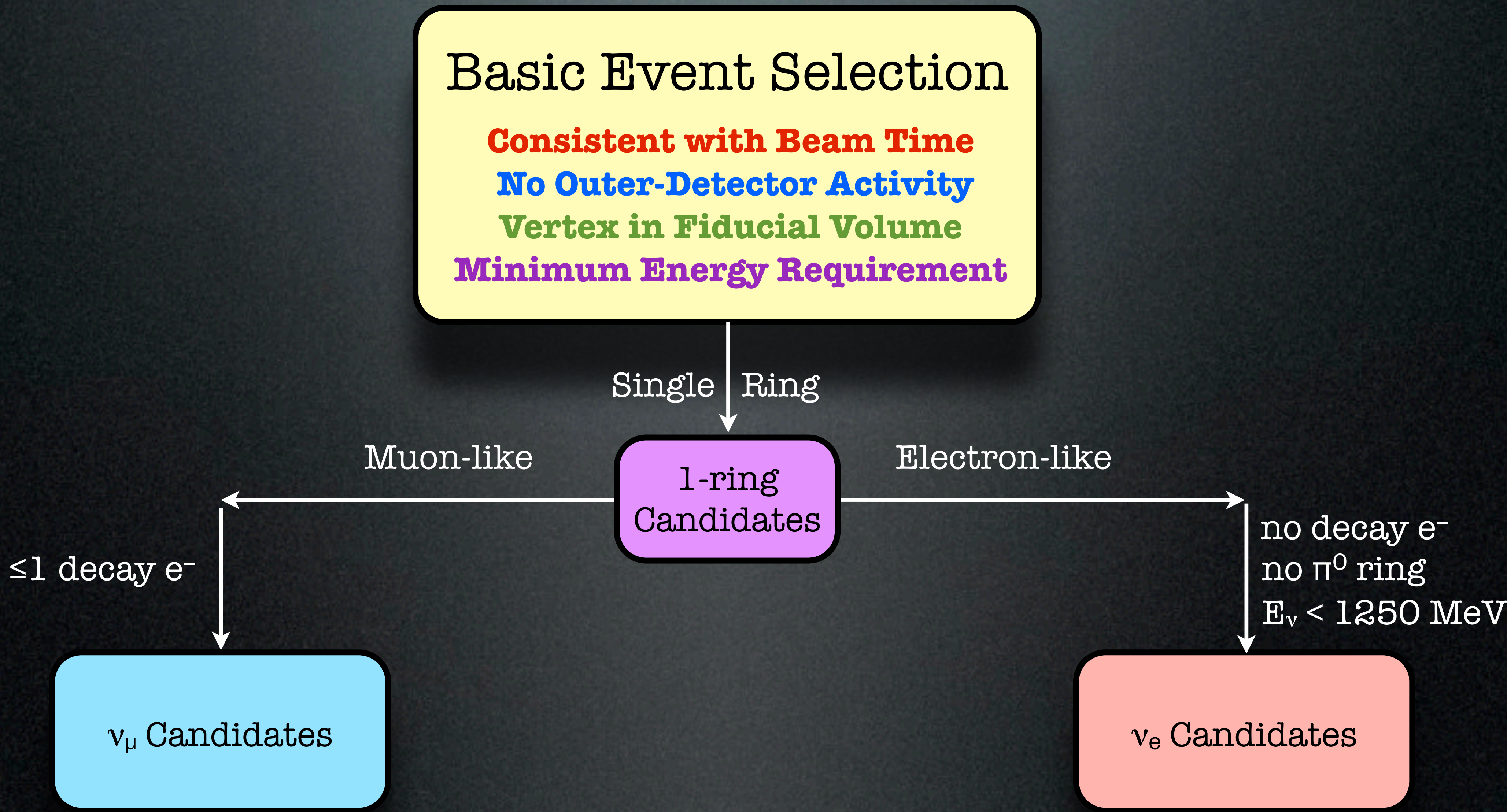
- 4.92 ± 0.55 background events
- 21.6 ± 1.9 events expected
  - For $\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$, and normal mass hierarchy
  - **5.5σ sensitivity to exclude $\theta_{13} = 0$**
- Oscillation parameters were extracted in 2 different ways:
  - using the E_ν distribution
  - using the p-θ distribution



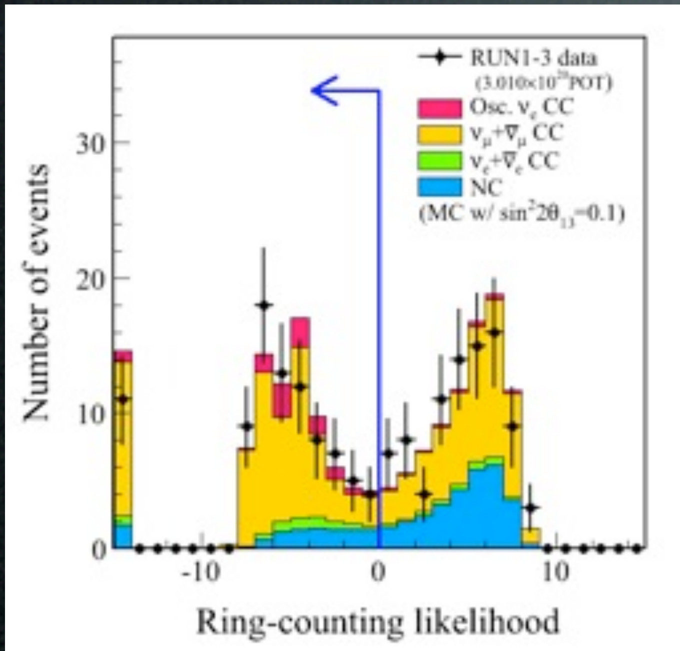


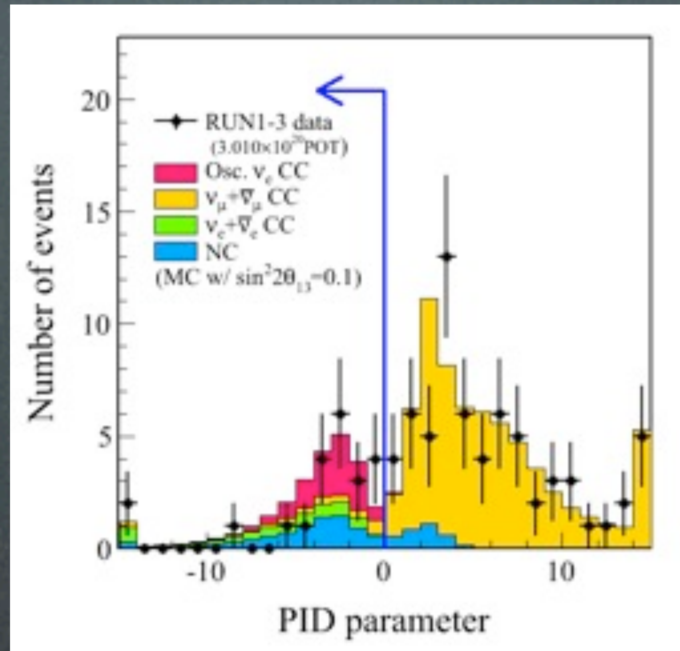
Super K Event Selection

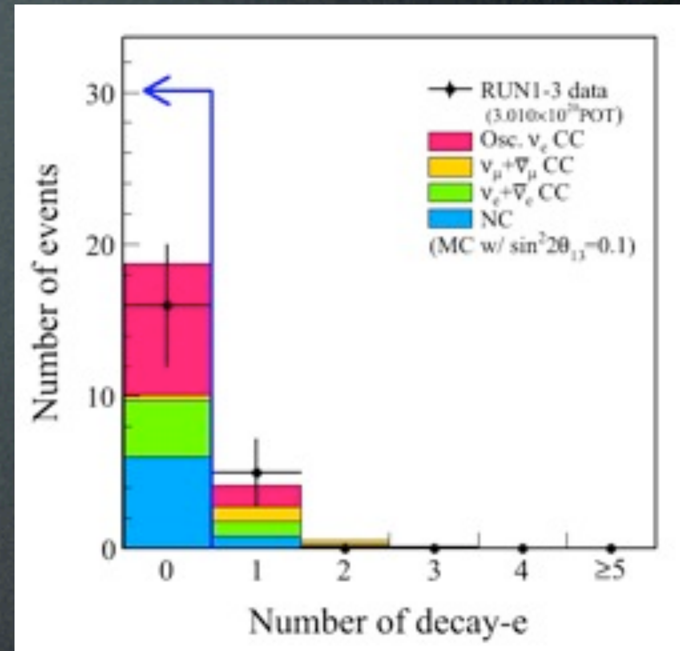
- Cuts were set before looking at the data
- This is possible because Super K is already a well-understood detector

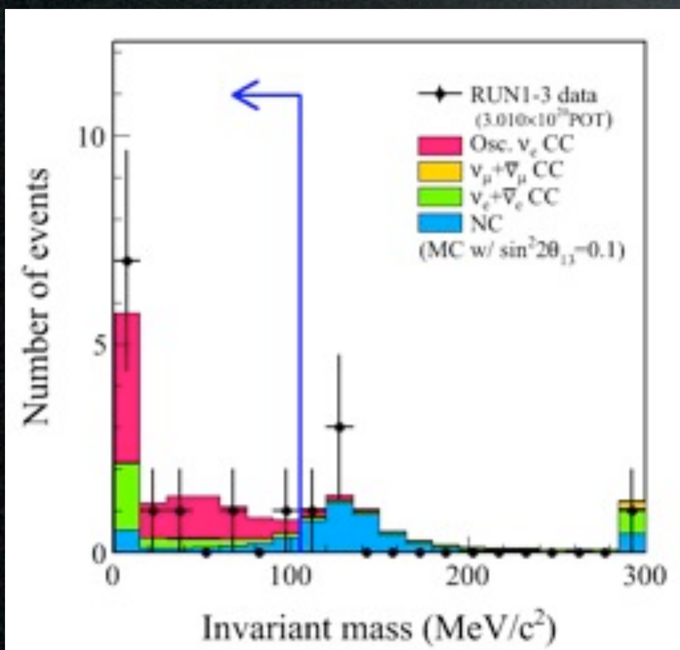


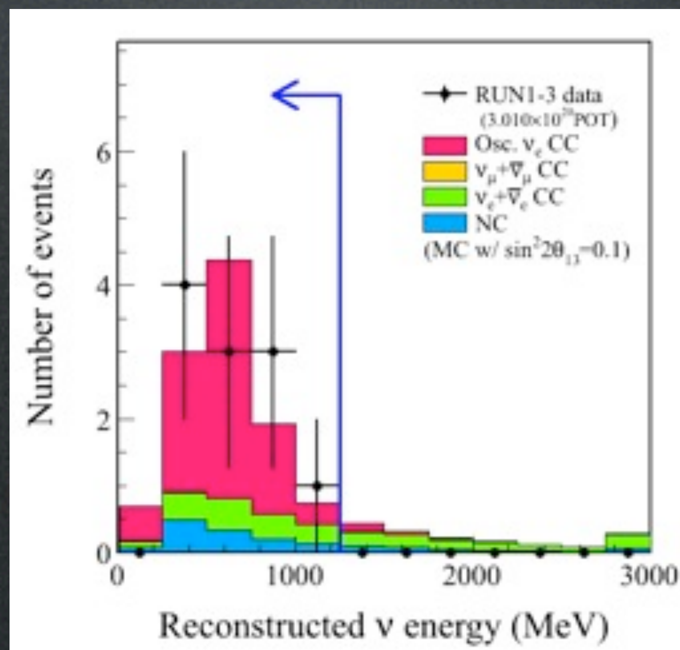
ν_e Appearance Selection







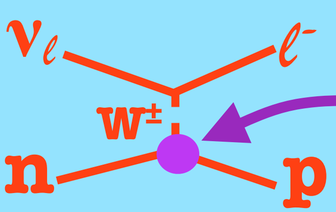




Results from data set through 2012

Cross Section Model

CCQE



Main difficulty is in understanding the hadronic current

However, the vector form factors are known from electron scattering!

- Remaining axial vector form factor has 2 parameters
- $F_A(0)$ is known from beta decay experiments
- M_A is the only free

$$F_A(Q^2) = \frac{F_A(0)}{(1 + \frac{Q^2}{M_A^2})^2}$$

$CC\pi^+$

- More complicated (and ad hoc)
- Has its own M_A parameter
- Pion-less Δ decay added by hand

Nuclear Model

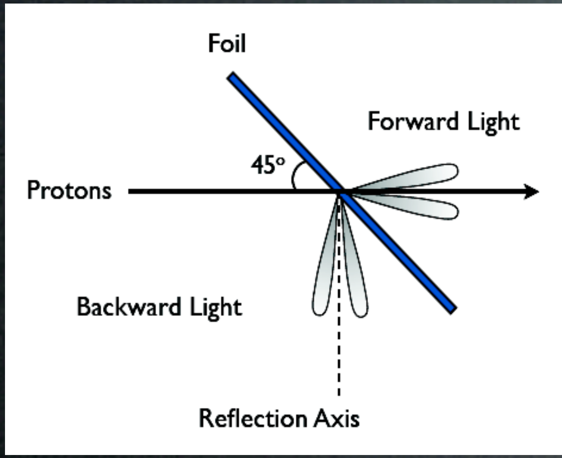
- Relativistic Fermi Gas (binding energy + p_{Fermi})
- Can also reweight to a spectral function treatment

Other

- Norm. factors are varied for other processes

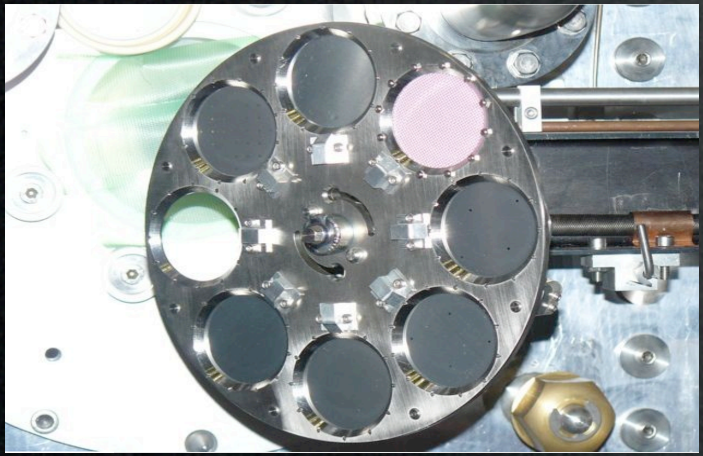
Parameter	E_ν Range	Nominal	Error	Class
M_A^{QE}	all	1.21 GeV/c^2	0.45	shape
M_A^{RES}	all	1.41 GeV/c^2	0.11	shape
p_F ^{12}C	all	217 MeV/c	30	shape
E_B ^{12}C	all	25 MeV	9	shape
SF ^{12}C	all	0 (off)	1 (on)	shape
CC Other shape ND280	all	0.0	0.40	shape
Pion-less Δ Decay	all	0.0	0.2	shape
CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11	norm
CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30	norm
CCQE E3	$E_\nu > 3.5$	1.0	0.30	norm
CC1π E1	$0 < E_\nu < 2.5$	1.15	0.43	norm
CC1π E2	$E_\nu > 2.5$	1.0	0.40	norm
CC Coh	all	1.0	1.0	norm
NC1π^0	all	0.96	0.43	norm
NC 1$\pi^\pm$	all	1.0	0.3	norm
NC Coh	all	1.0	0.3	norm
NC other	all	1.0	0.30	norm
ν_μ/ν_e	all	1.0	0.03	norm
$\nu/\bar{\nu}$	all	1.0	0.40	norm

Proton Beam Monitoring

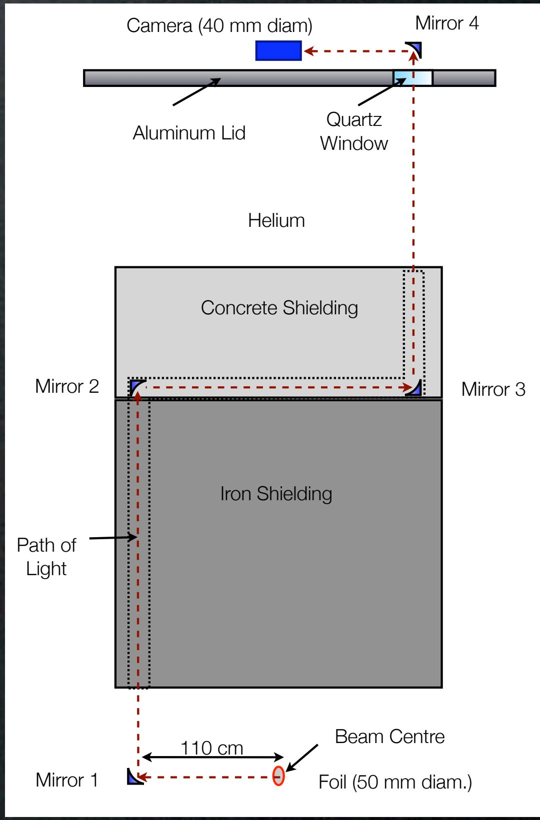


- A series of beam monitors measure the mean beam position along the length of the beamline
- The final monitor, attached to the horn assembly, is OTR (Optical Transition Radiation monitor)
- Titanium foils oriented at 45° relative to the beamline produce reflected light perpendicular to the beam direction

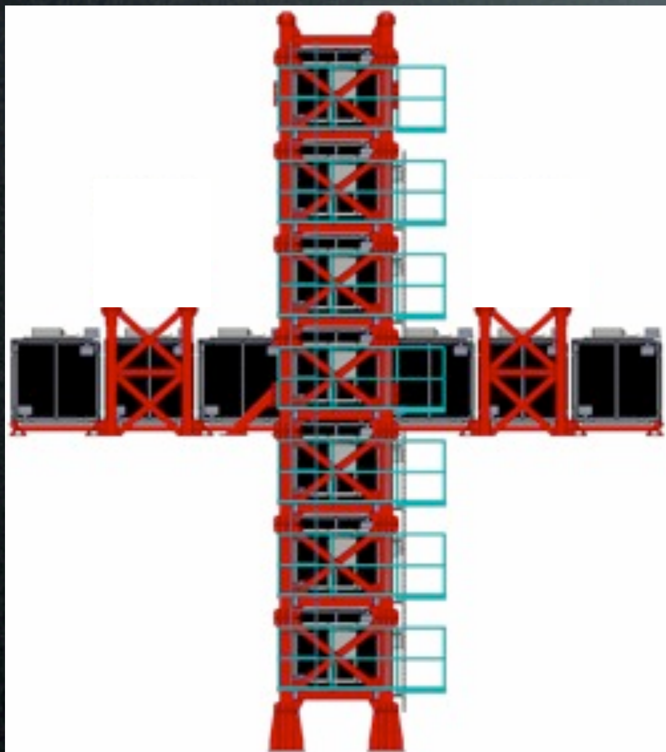
- The reflected light is guided along small passages through the shielding by a series of mirrors
- The shape and position of the beam are imaged by a 40 mm camera



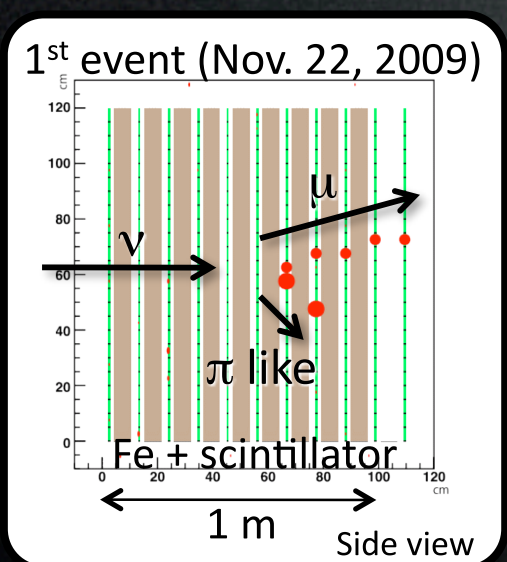
- Built by Unversity of Toronto, York University, and TRIUMF

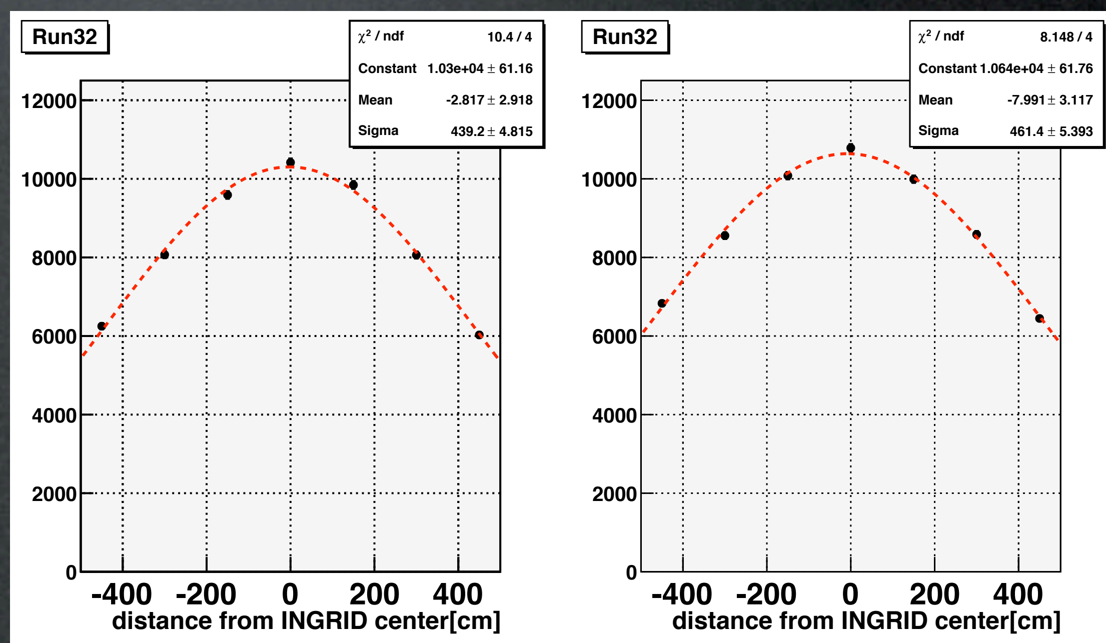


INGRID



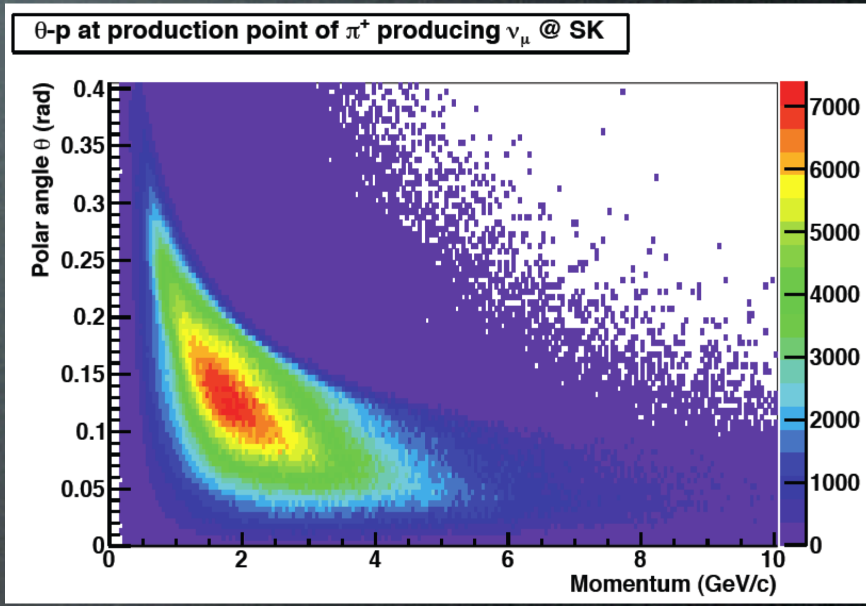
- Located on-axis to measure the beam direction
- 14 modules of alternating iron and scintillator, arranged in a cross
- Rate of interactions is measured in each module
  - Fit to Gaussian to determine bin center
- Beam direction determined to better than 0.5 mrad



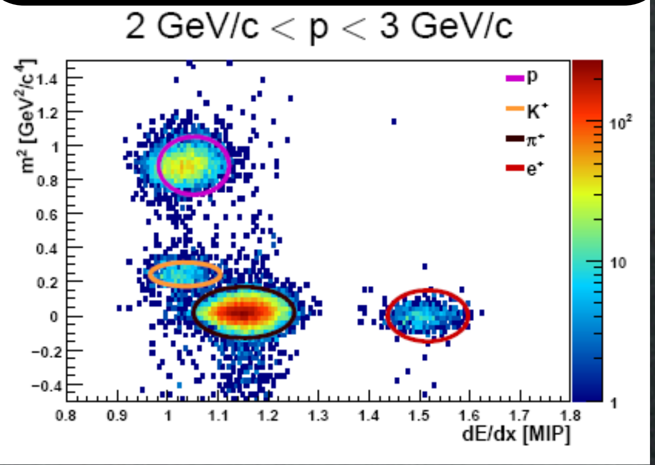


Constraining the ν Flux

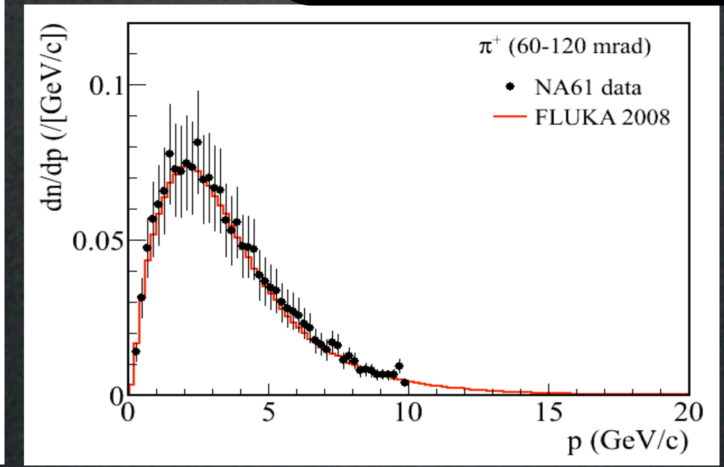
- The dominant flux uncertainties are in π/K production from p+C interactions
- "Sweet spot" for producing neutrinos at Super K (due to horn focusing)
- The NA61 experiment at CERN has taken data on a thin C target and a T2K replica target
  - Good particle separation from combined time-of-flight and dE/dx measurements
  - T2K flux has been tuned to match differential pion production cross sections

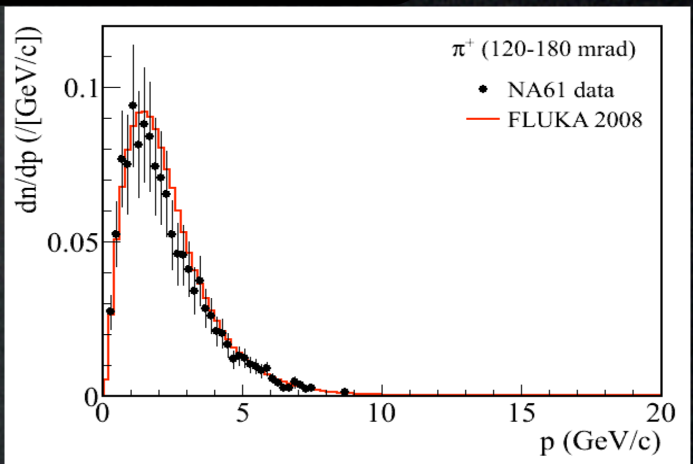


NA61 Particle ID



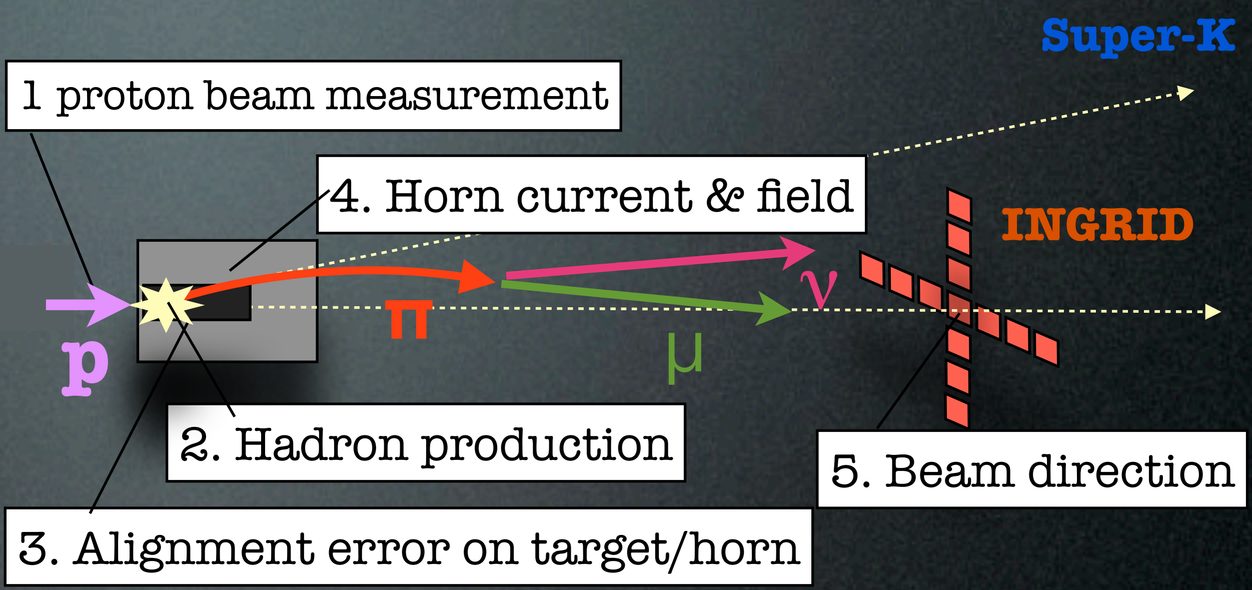
NA61 Data vs FLUKA

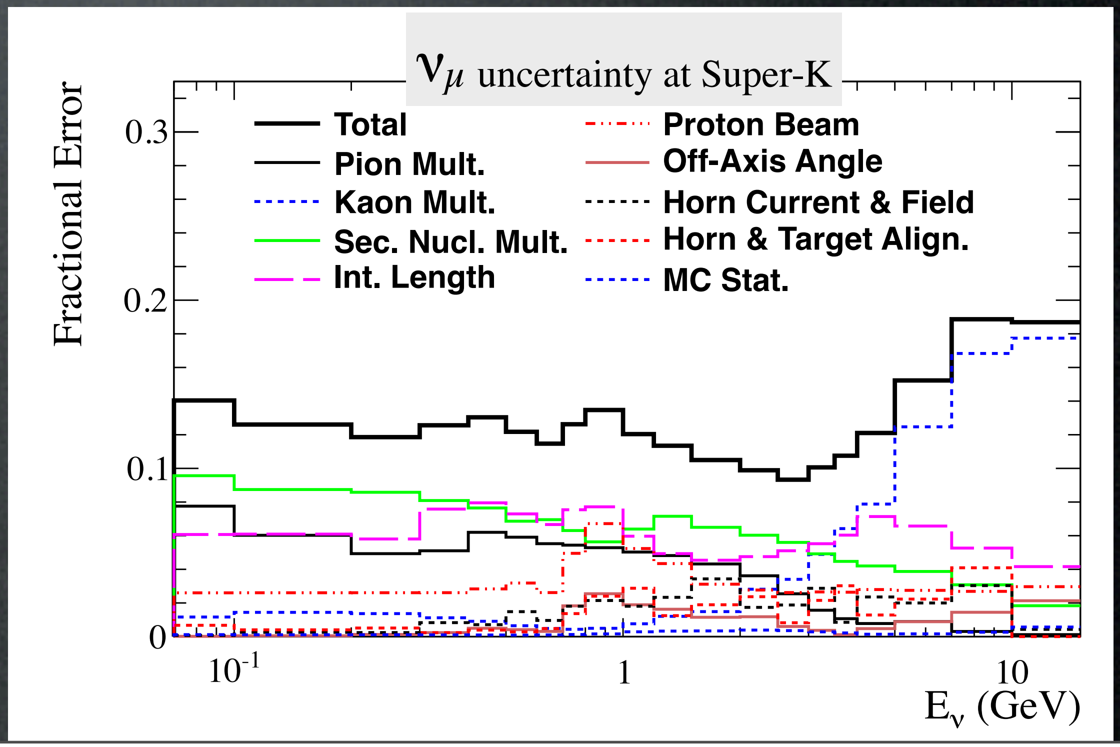




ν Flux Uncertainties

1. **Measurement error on monitoring proton beam**
2. **Hadron production**
3. **Alignment error on the target and the horn**
4. **Horn current & field**
5. **Neutrino beam direction (Off-axis angle)**

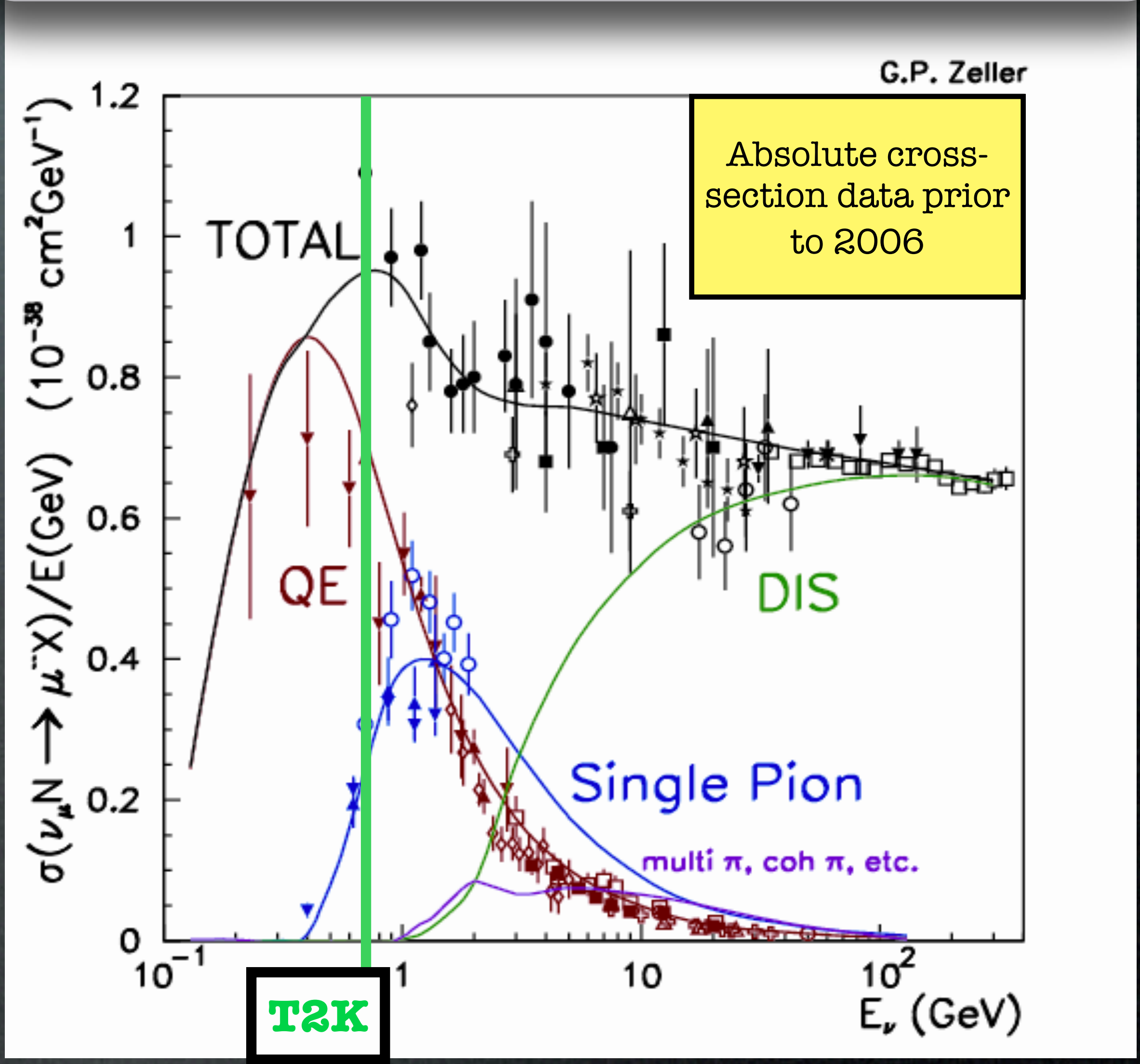




Neutrino Cross Sections

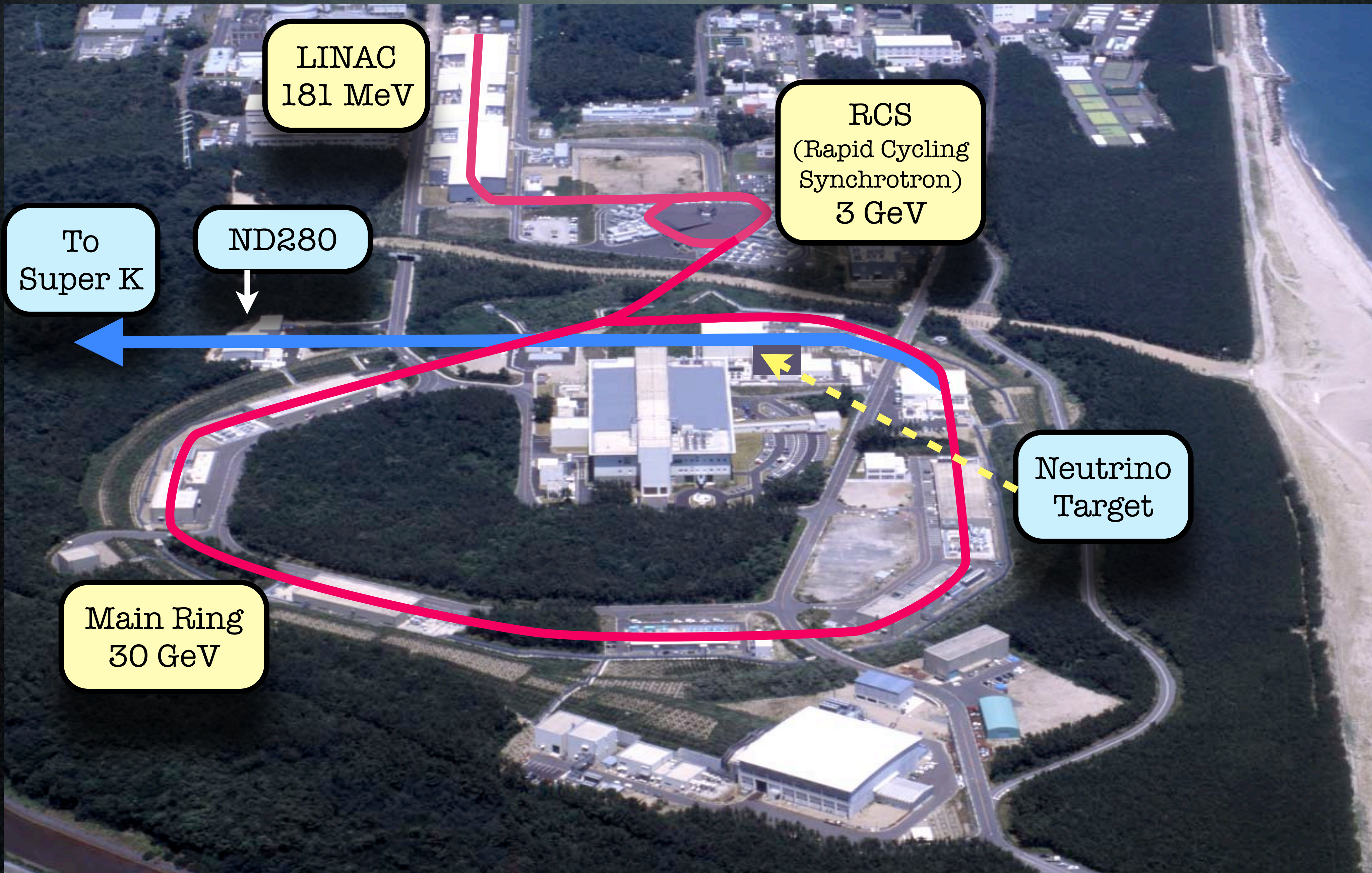
- At T2K peak neutrino energy, **CCQE is the dominant** interaction
  - $CC\pi^+$ is a significant background
  - At higher energies, multi-pion and deep inelastic scattering (DIS) become important
- Before 2006, **very few neutrino cross section data sets** were available at low energies
  - Only a few thousand events
  - No nuclear targets below 3 GeV (D_2 and H_2 measurements)
  - Often inconsistent results
- More recent data with high statistics on nuclear targets is now available
  - T2K makes significant use of MiniBooNE cross section measurements

Charged Current Cross Sections

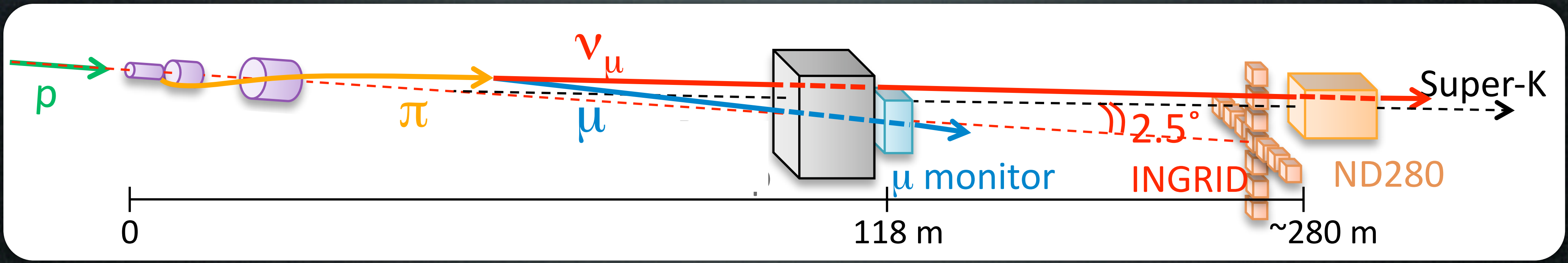


J-PARC

(Japan Particle Acclerator Research Complex)



The Neutrino Beam



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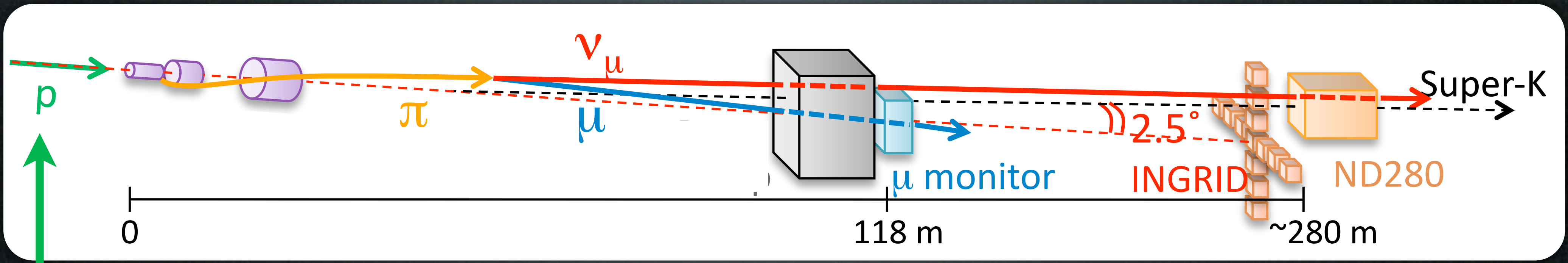
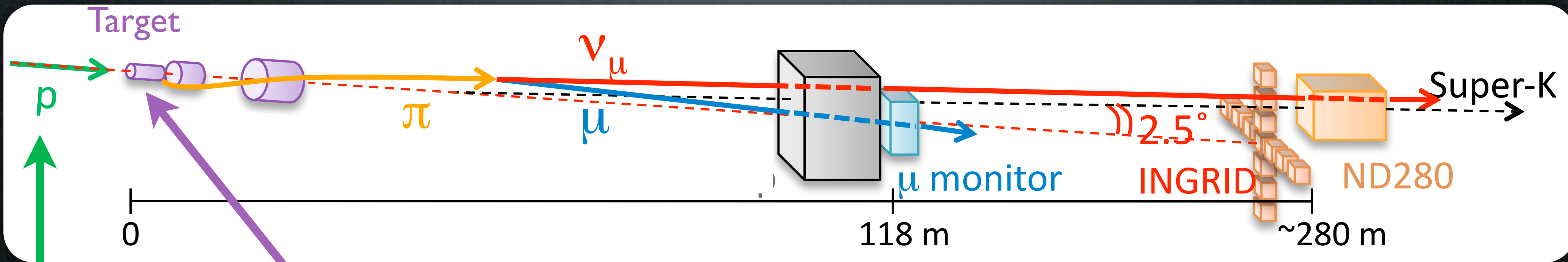


30 GeV protons from the J-PARC Accelerator

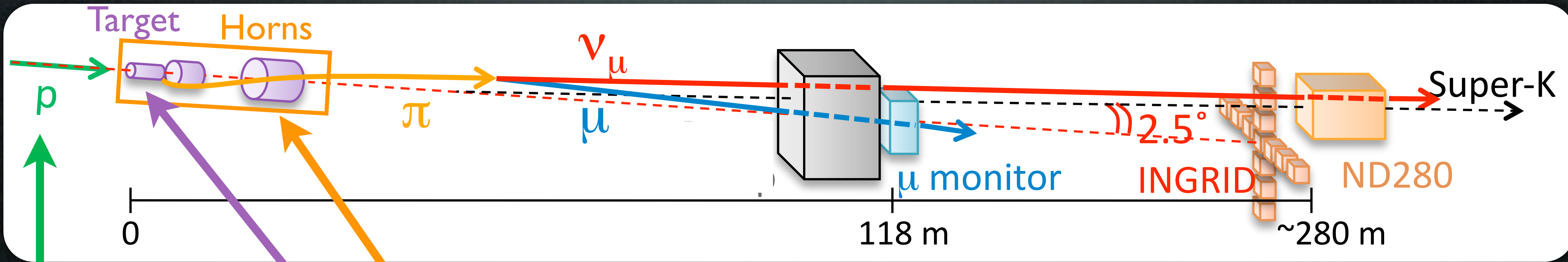
The Neutrino Beam



30 GeV protons from the J-PARC Accelerator

Protons interact in a 90cm graphite target

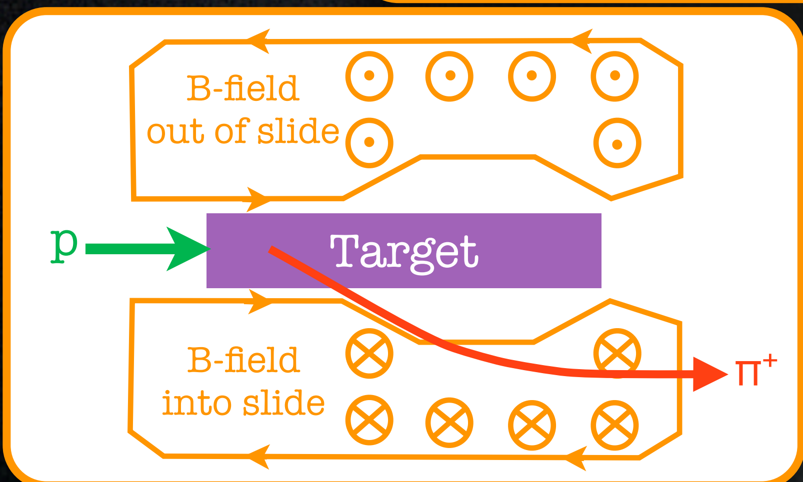
The Neutrino Beam



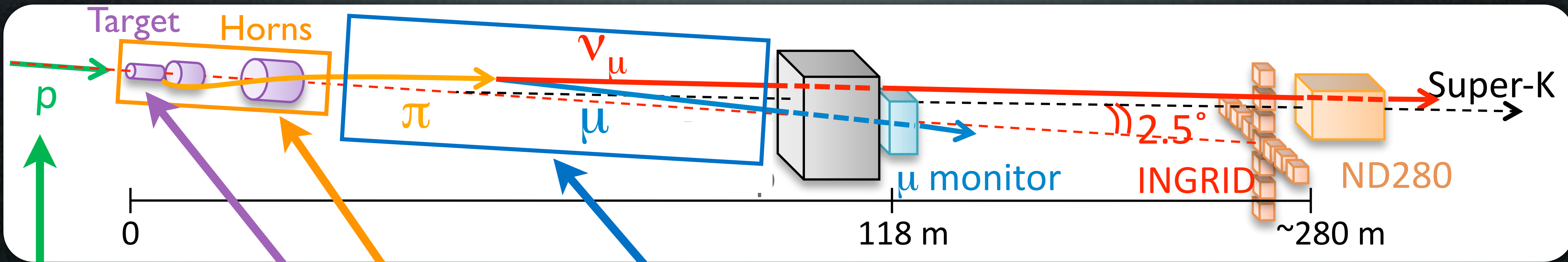
30 GeV protons from the J-PARC Accelerator

Protons interact in a 90cm graphite target

Resulting Pions are forward-focused by the toroidal B-field within 3 "horns"



The Neutrino Beam



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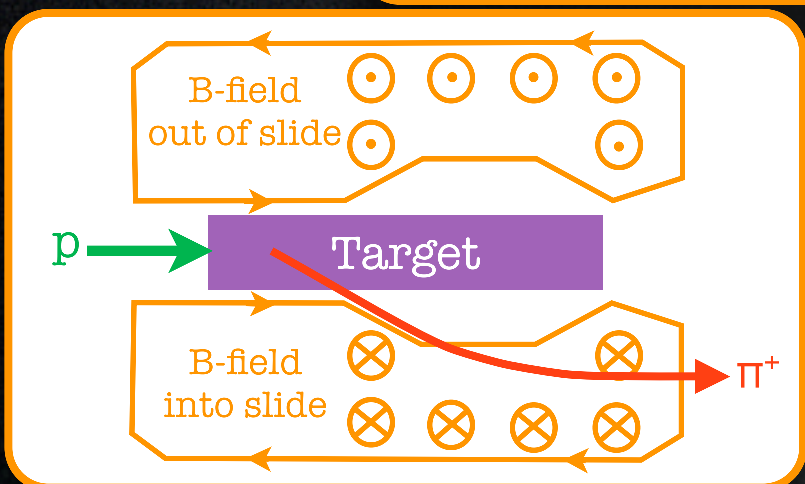
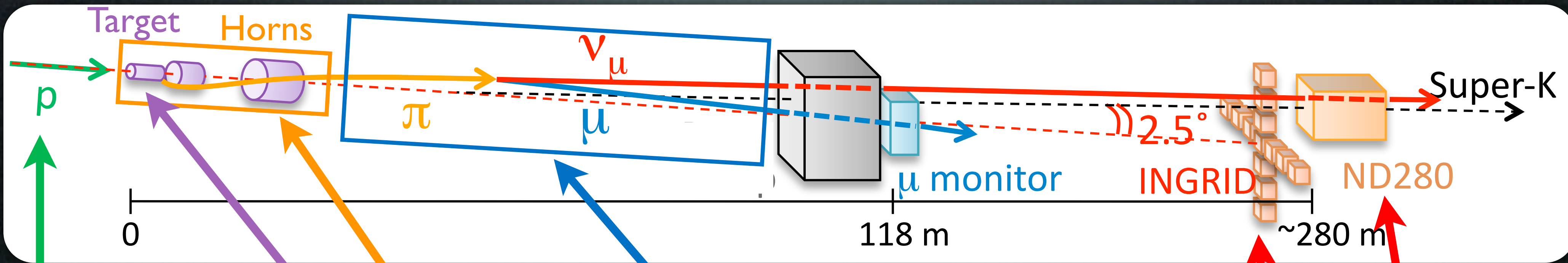
Pions decay to μ and ν_μ within a 100m decay volume



The Neutrino Beam



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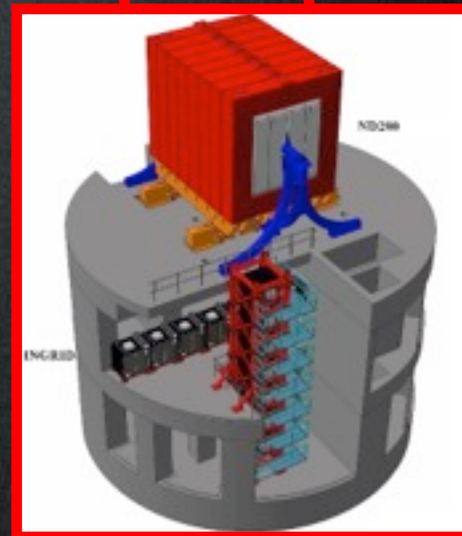

The resulting beam of neutrinos is directed at the on-axis detector: INGRID

The off-axis detector, ND280, sits between the target and Super-K: 2.5° off the mean beam direction